Kavli IPMU APEC seminar, The University of Tokyo (Japan), 11 May 2018

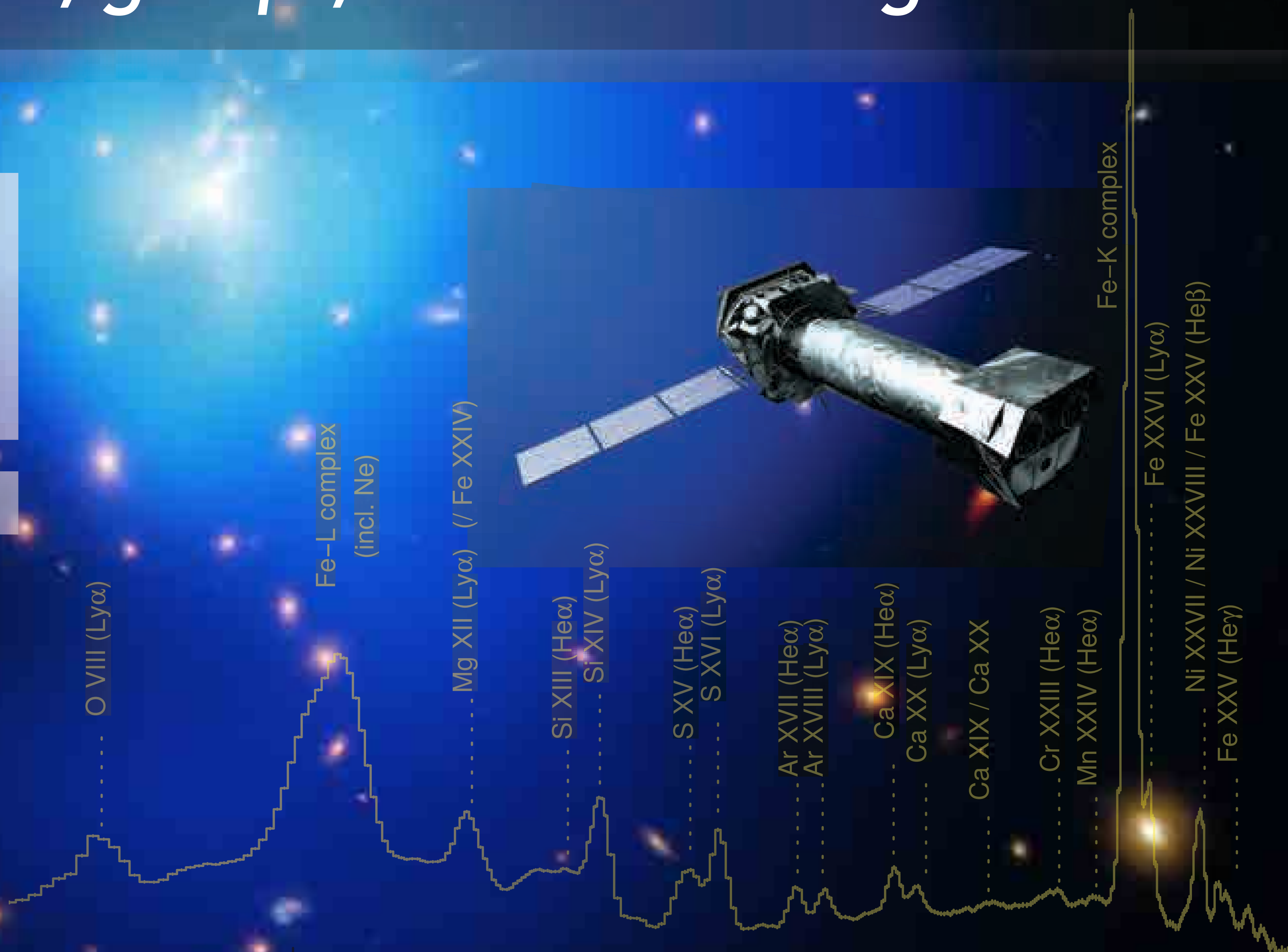
Understanding the chemical enrichment pattern in the hot haloes of massive ellipticals, groups, and clusters of galaxies

François Mernier

フランソワ メェニェー

N. Werner, J. de Plaa, A. Simionescu, and the CHEERS collaboration

MTA-Eötvös University, Budapest

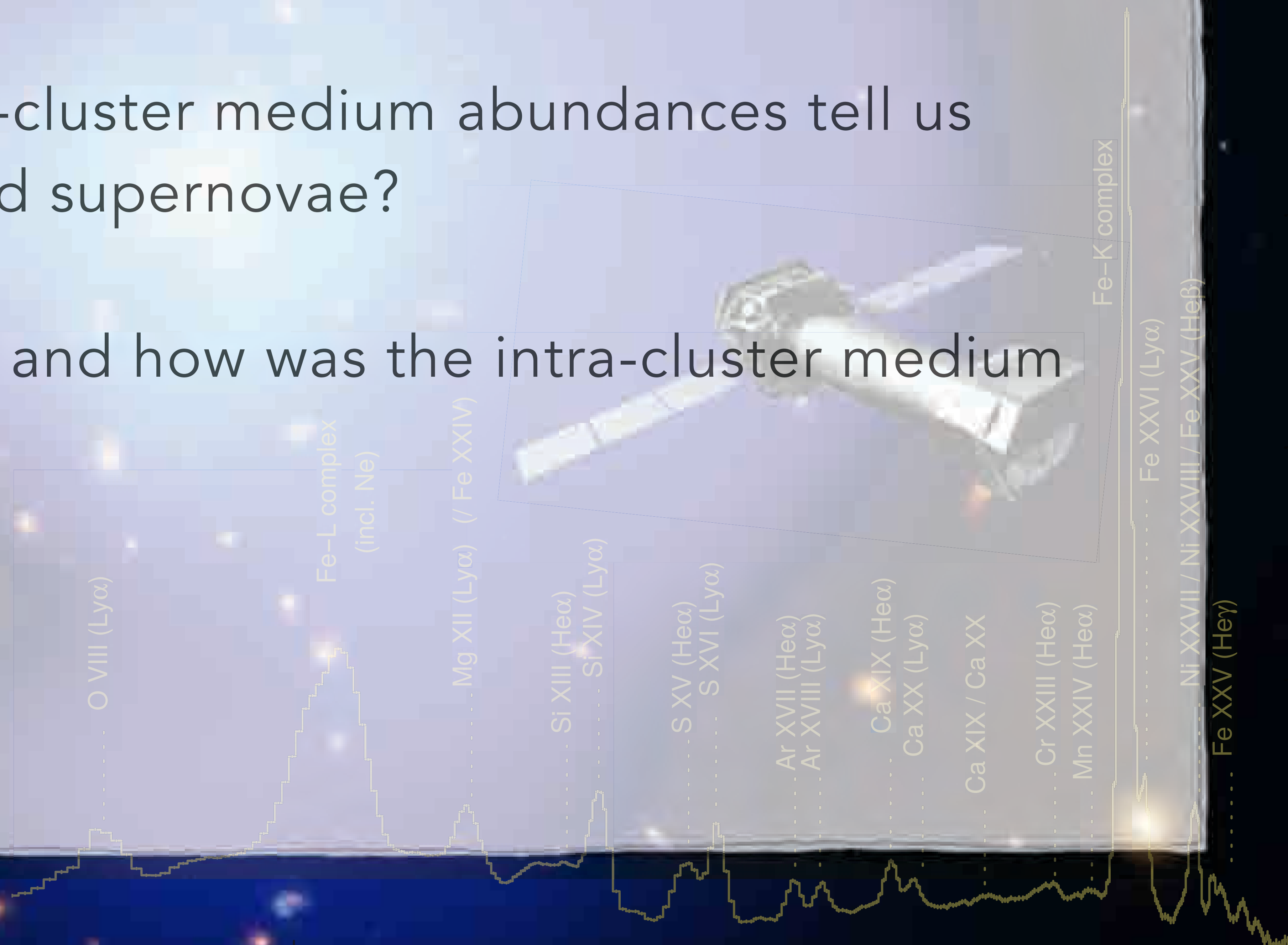


SRON

Netherlands Institute for Space Research

Outline

- Introduction
- 1. What do intra-cluster medium abundances tell us about stars and supernovae?
- 2. Where, when, and how was the intra-cluster medium enriched?
- Future missions
- Conclusions

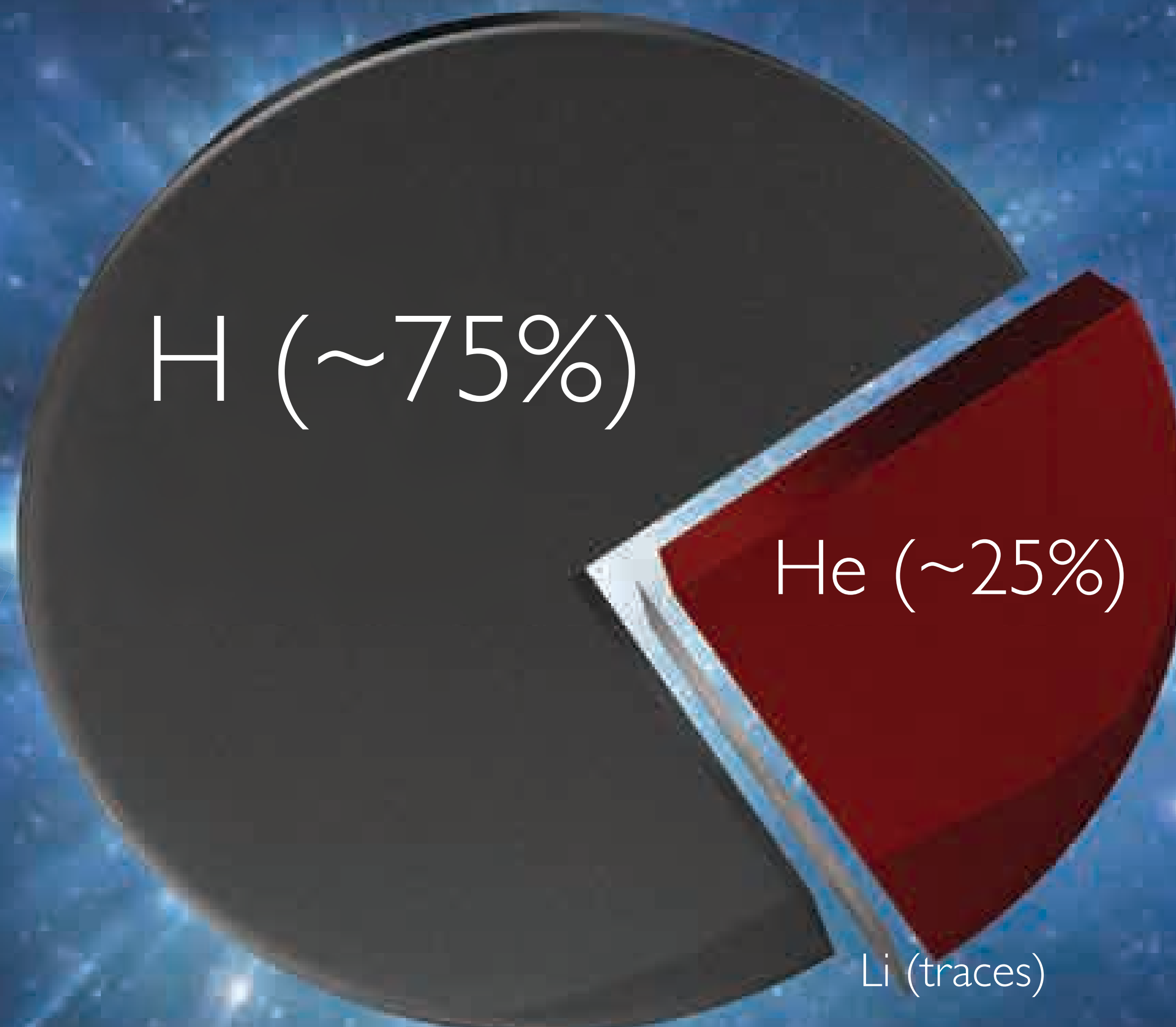


Introduction

The origin of chemical elements

Where do chemical elements come from?

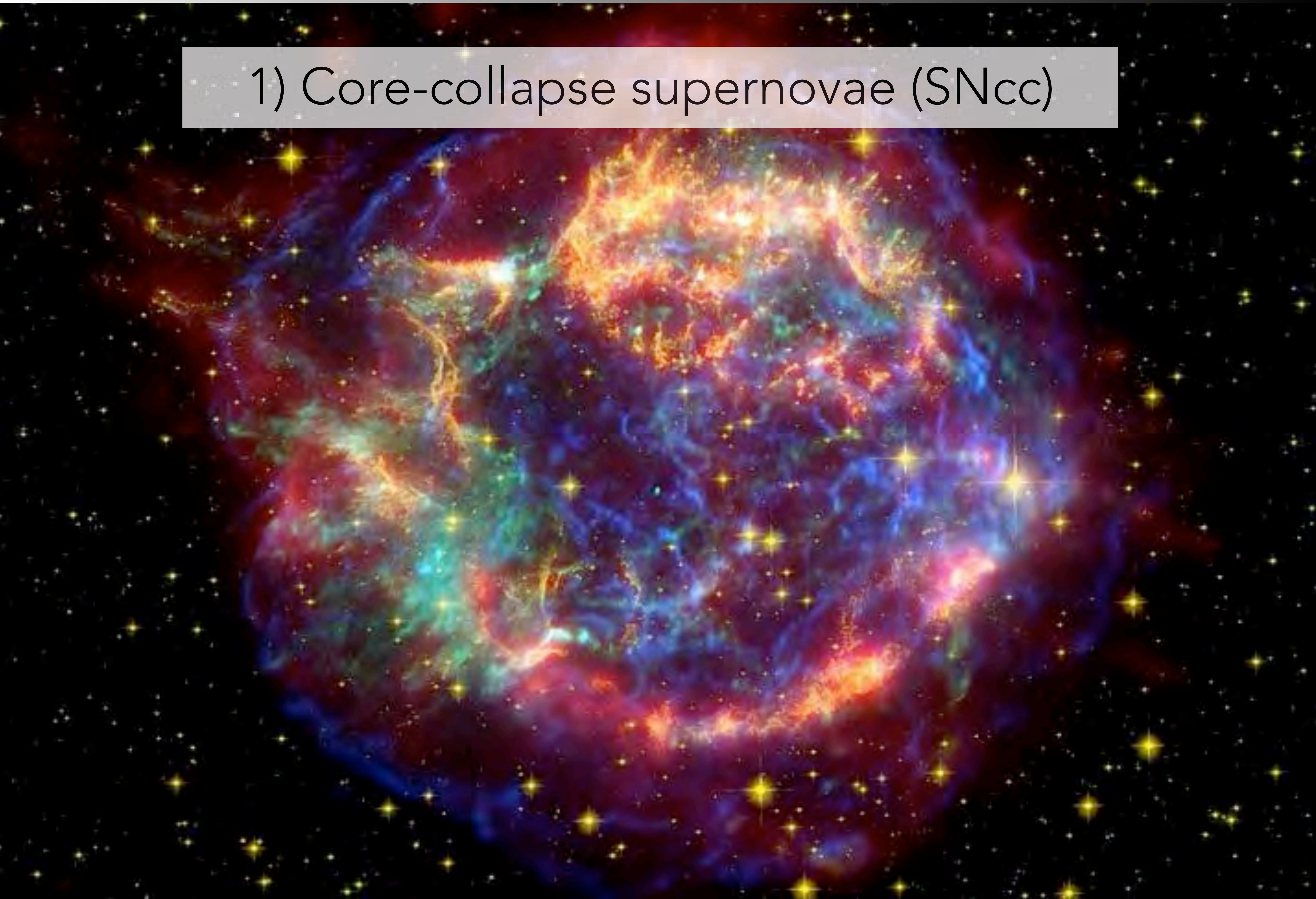
Primordial nucleosynthesis



How about heavier elements (=metals)?

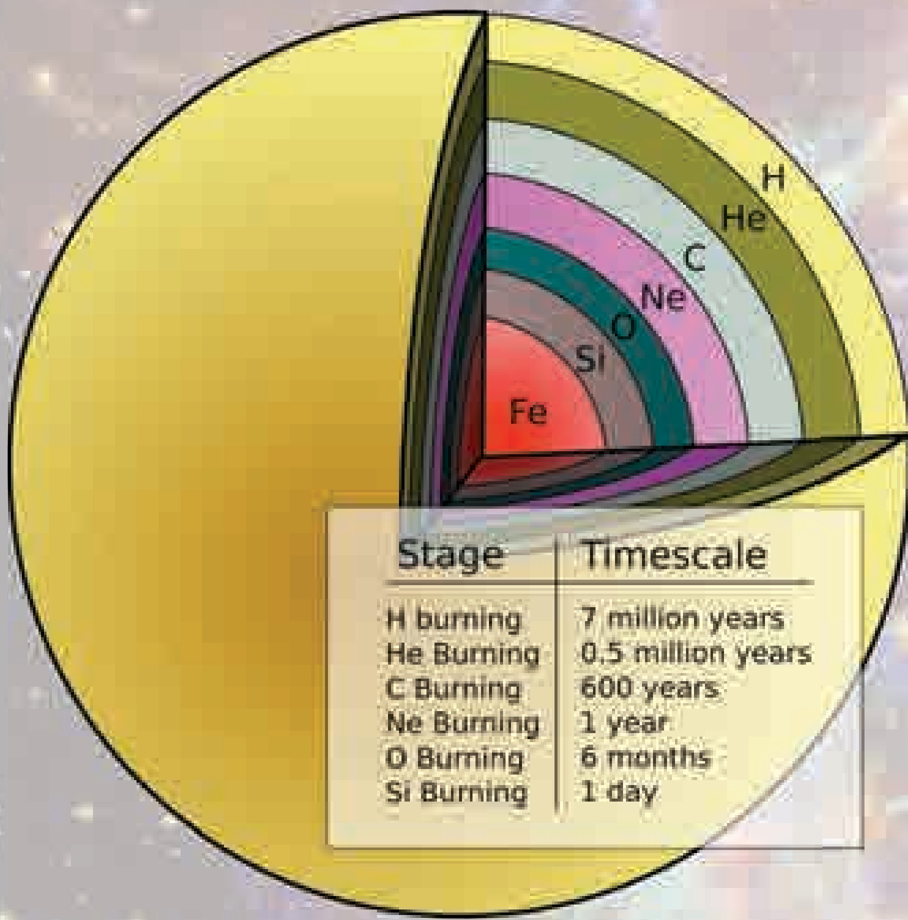
The origin of chemical elements

1) Core-collapse supernovae (SNcc)



The origin of chemical elements

1) Core-collapse supernovae (SNcc)



Explode (and enrich) quite fast after star formation

Produces:

➡ ***O***

➡ ***Ne***

➡ ***Mg***

➡ ***Si***

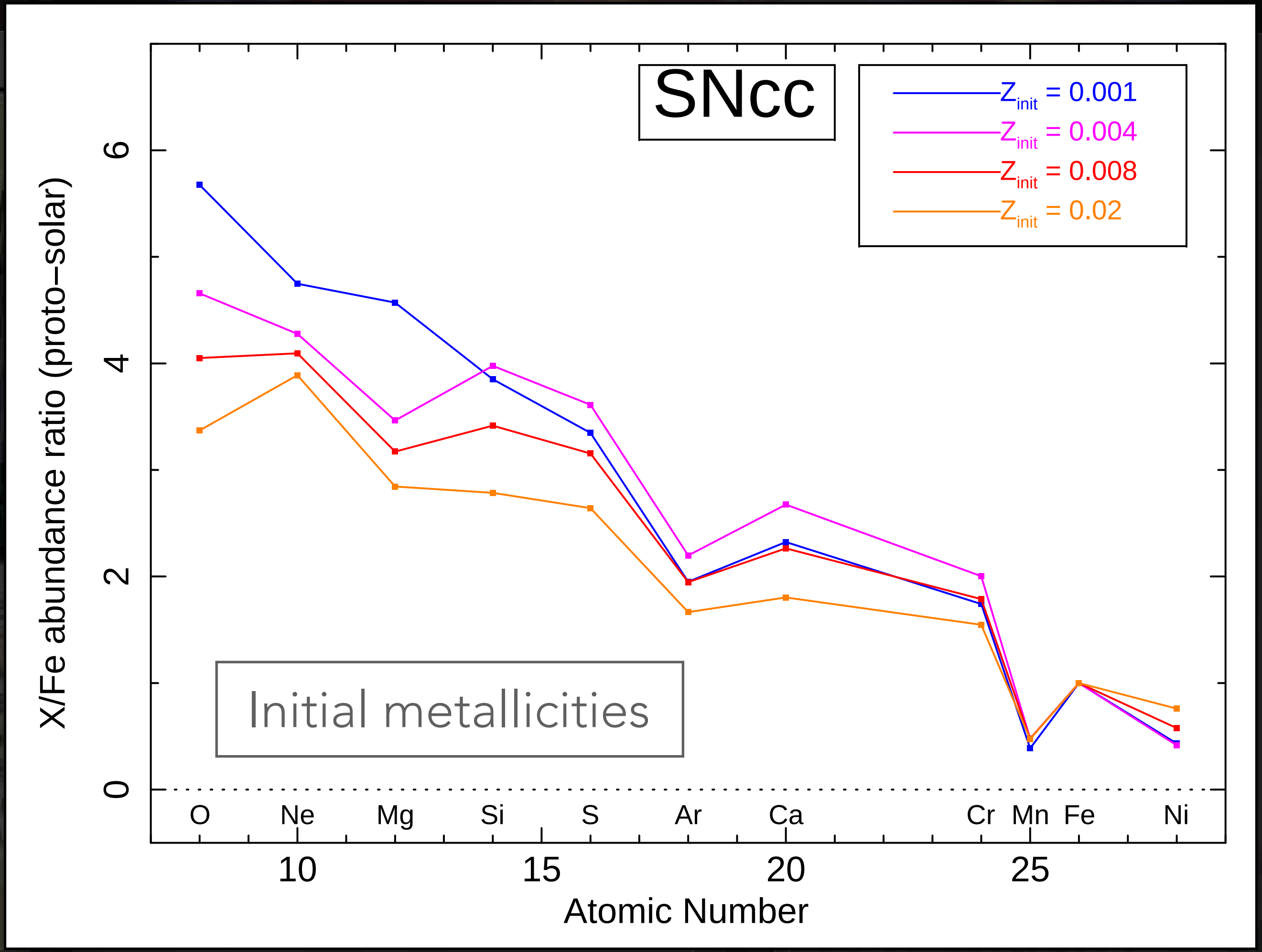
How much? Depends on:

➡ Mass of the star (➔ ***Initial mass function***)

➡ Initial metallicity of the star (Z_{init})

The origin of chemical elements

1) Core-collapse supernovae (SNcc)



adapted from Nomoto et al. (2013)

Explode (and enrich) quite fast after star formation

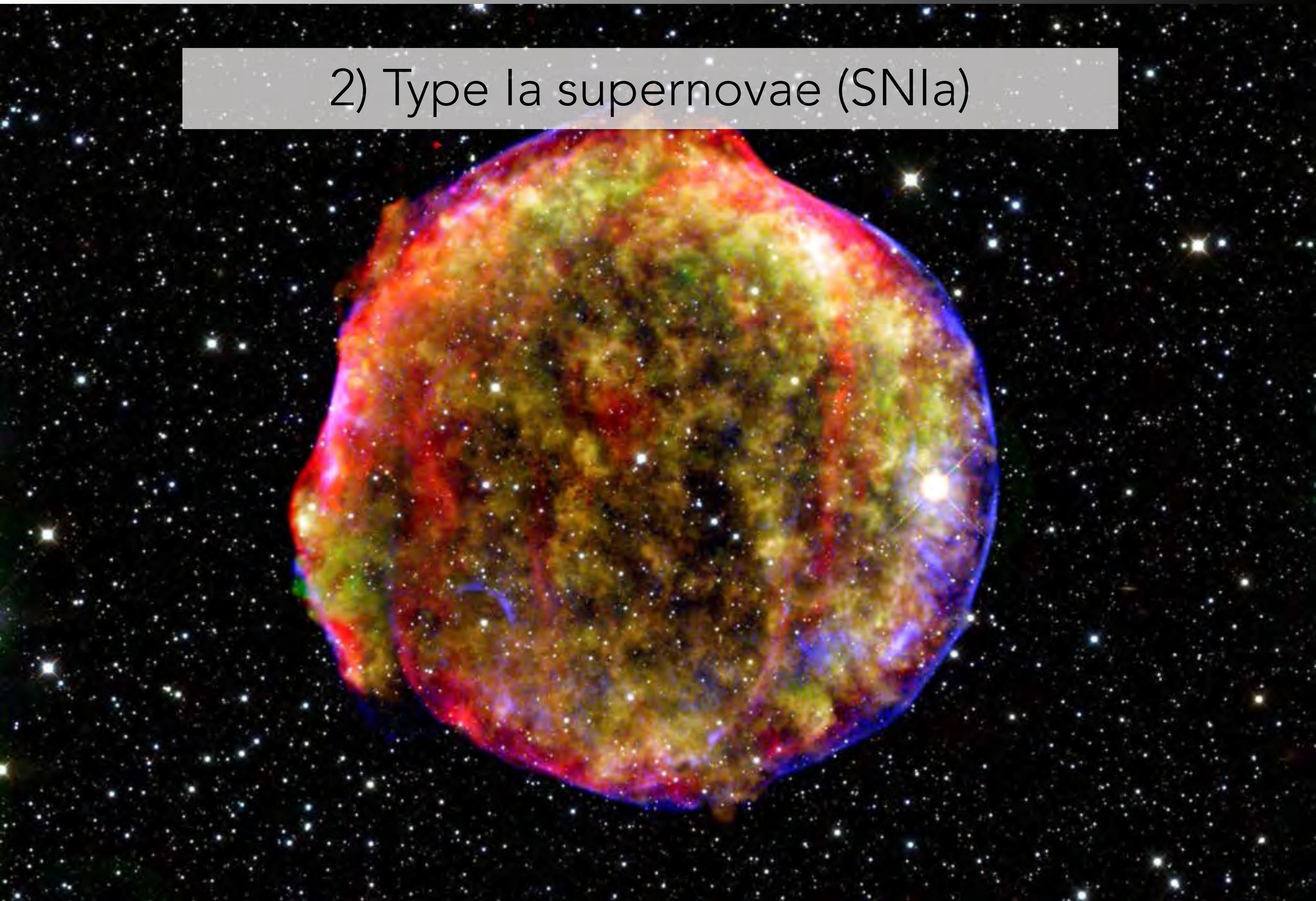
...pends on:

➡ Mass of the star (→ ***Initial mass function***)

➡ Initial metallicity of the star (Z_{init})

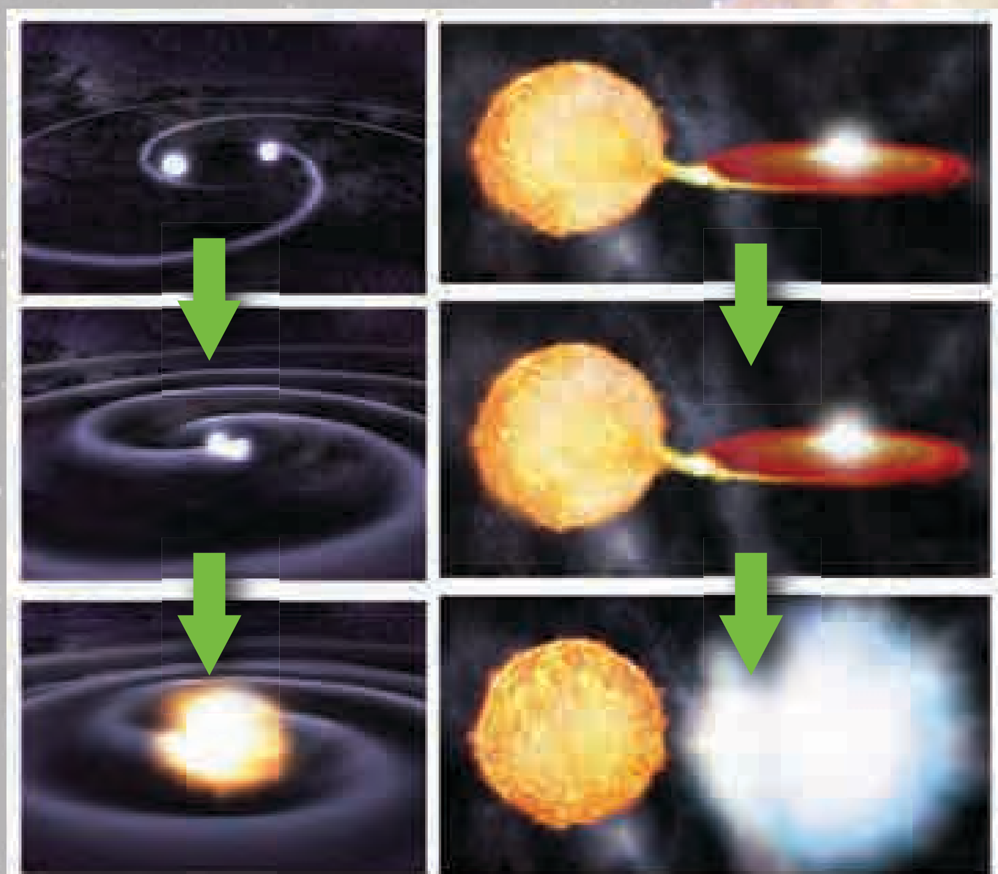
The origin of chemical elements

2) Type Ia supernovae (SNIa)



The origin of chemical elements

2) Type Ia supernovae (SNIa)



This? ...Or this?

Time delay between star formation and SNIa explosions (?)

Produces:

- ***Si***
- ***S***
- ***Ar***
- ***Ca***
- ***Fe***
- ***Ni***

How much? Depends on:

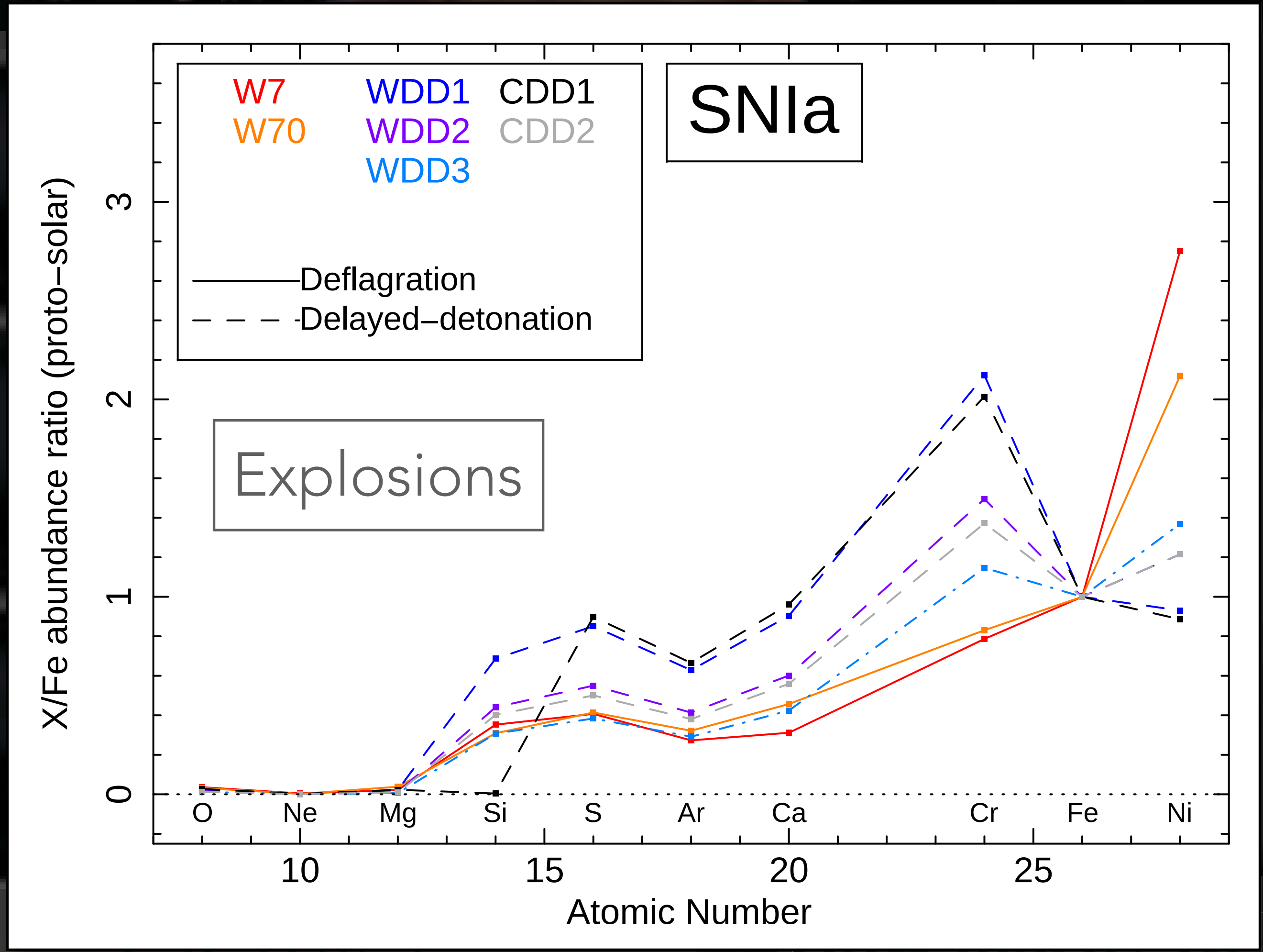
- Physics of the explosion (***deflagration*** vs. ***delayed-detonation***)

The origin of chemical elements

2) Type Ia supernovae (SNIa)

This?

...Or this?



adapted from Iwamoto et al. (1999)

Time delay between star formation and SNIa explosions (?)

➡ ***Ca***

➡ ***Fe***

➡ ***Ni***

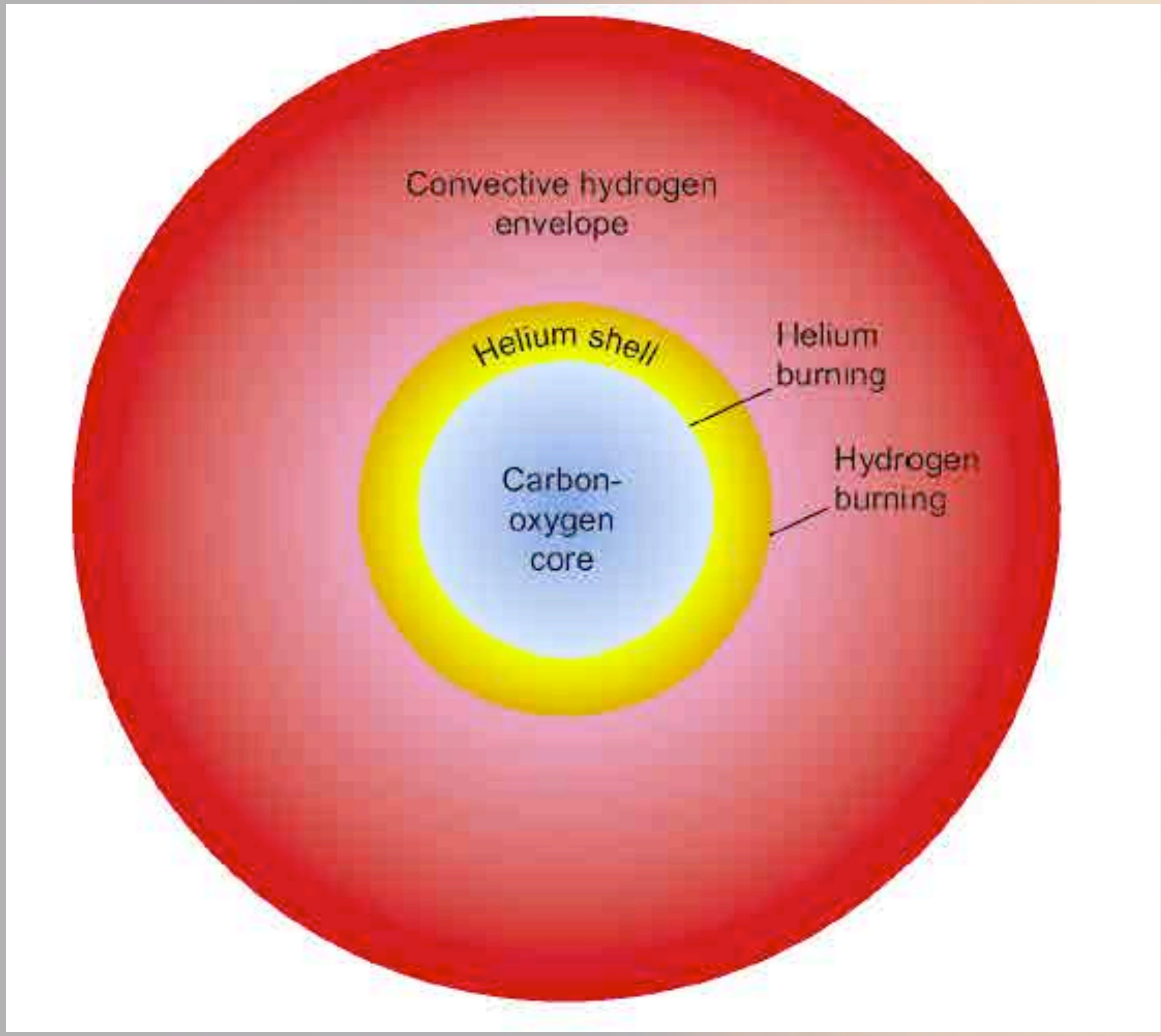
Depends on:

➡ Physics of the explosion

(***deflagration*** vs. ***delayed-detonation***)

The origin of chemical elements

3) Asymptotic Giant Branch stars (AGB)



Produces:

➡ ***C***

➡ ***N***

➡ traces of ***O***, ***Ne*** & ***Mg***

The origin of chemical elements

4) Merging neutron stars

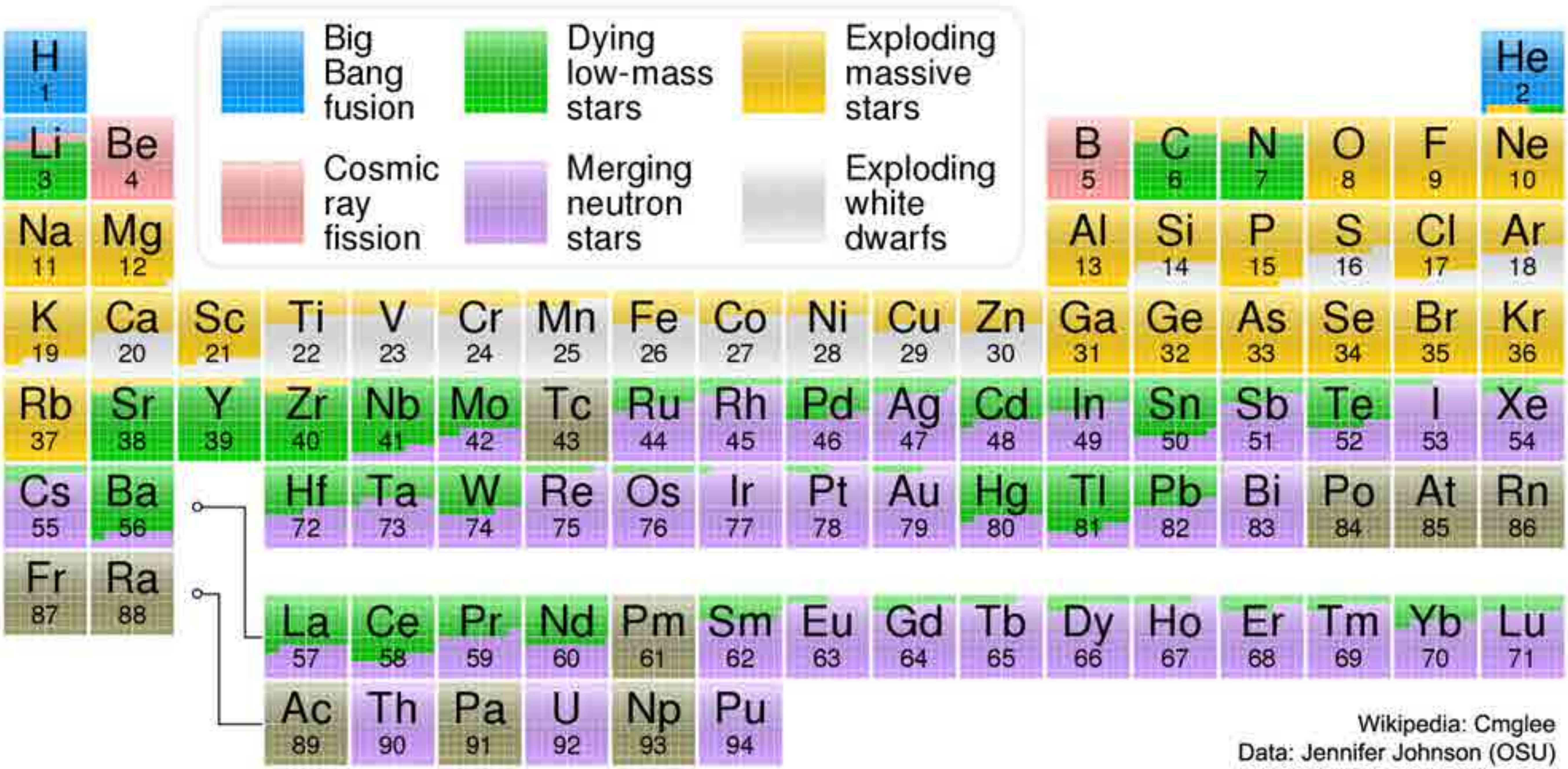
Produces:

➡ ***Heavier elements***

(Ag, Pt, Au,...)

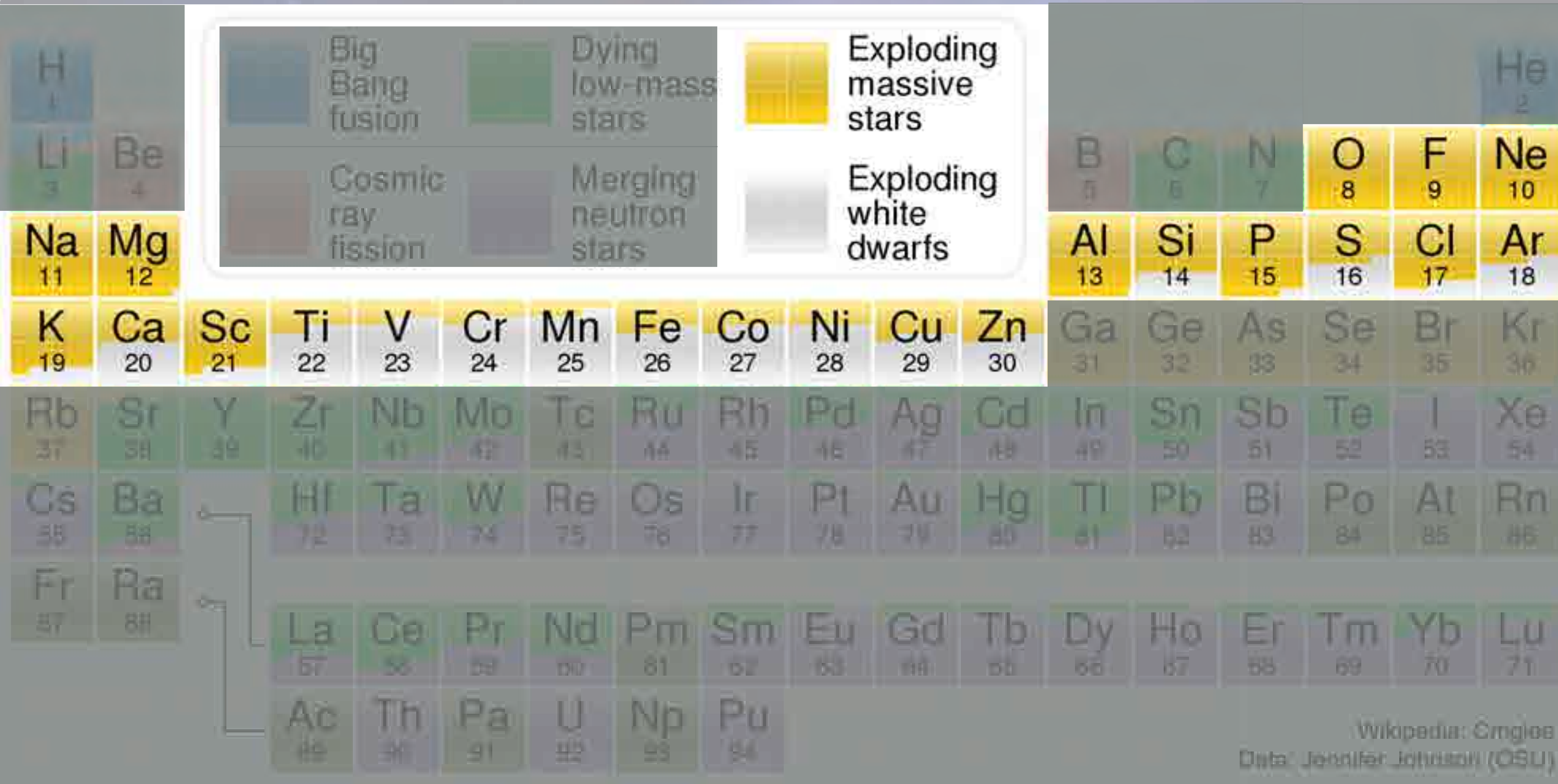
Recently confirmed thanks to LIGO!

The origin of chemical elements



We are all made of stars/supernovae!

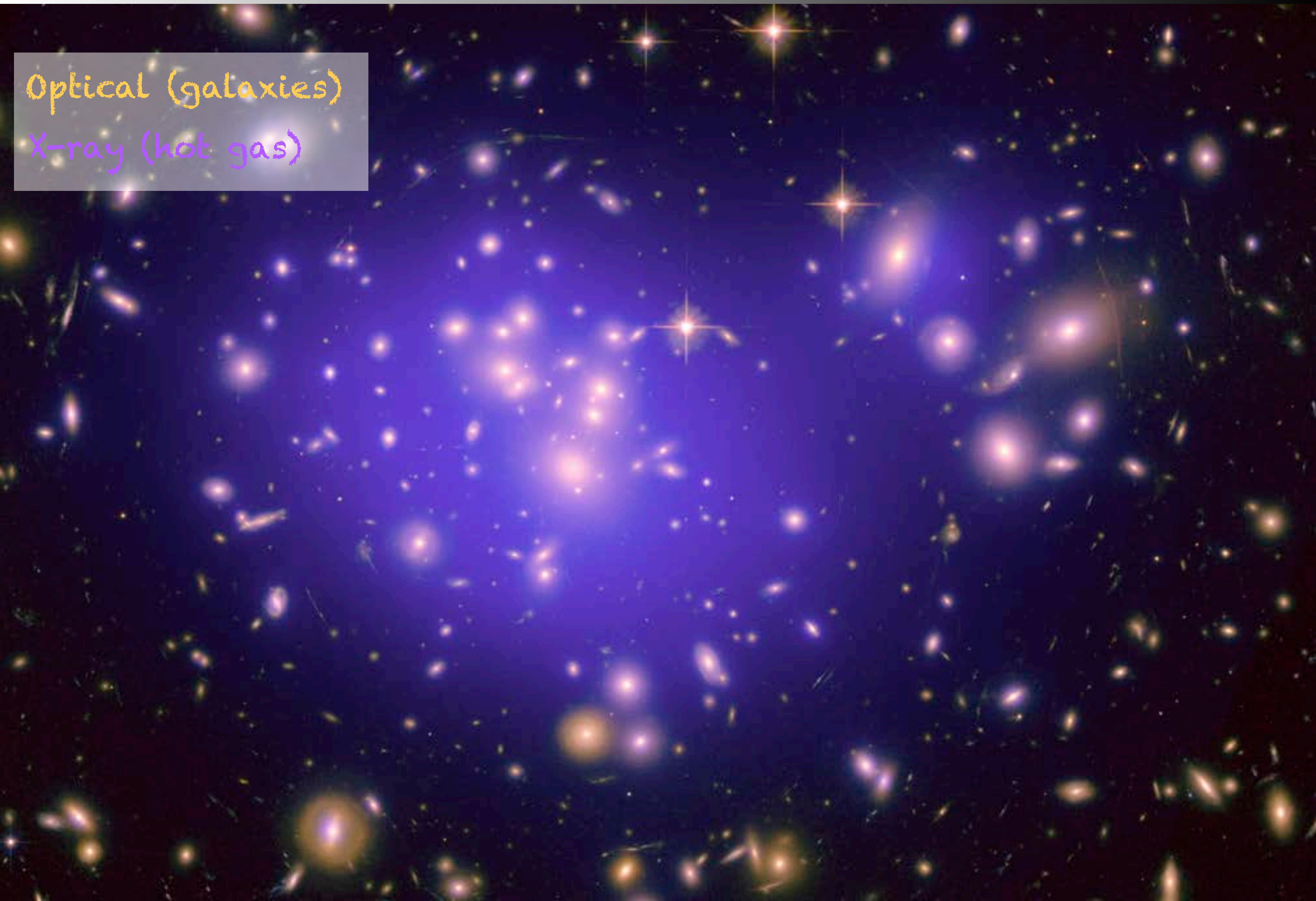
The origin of chemical elements



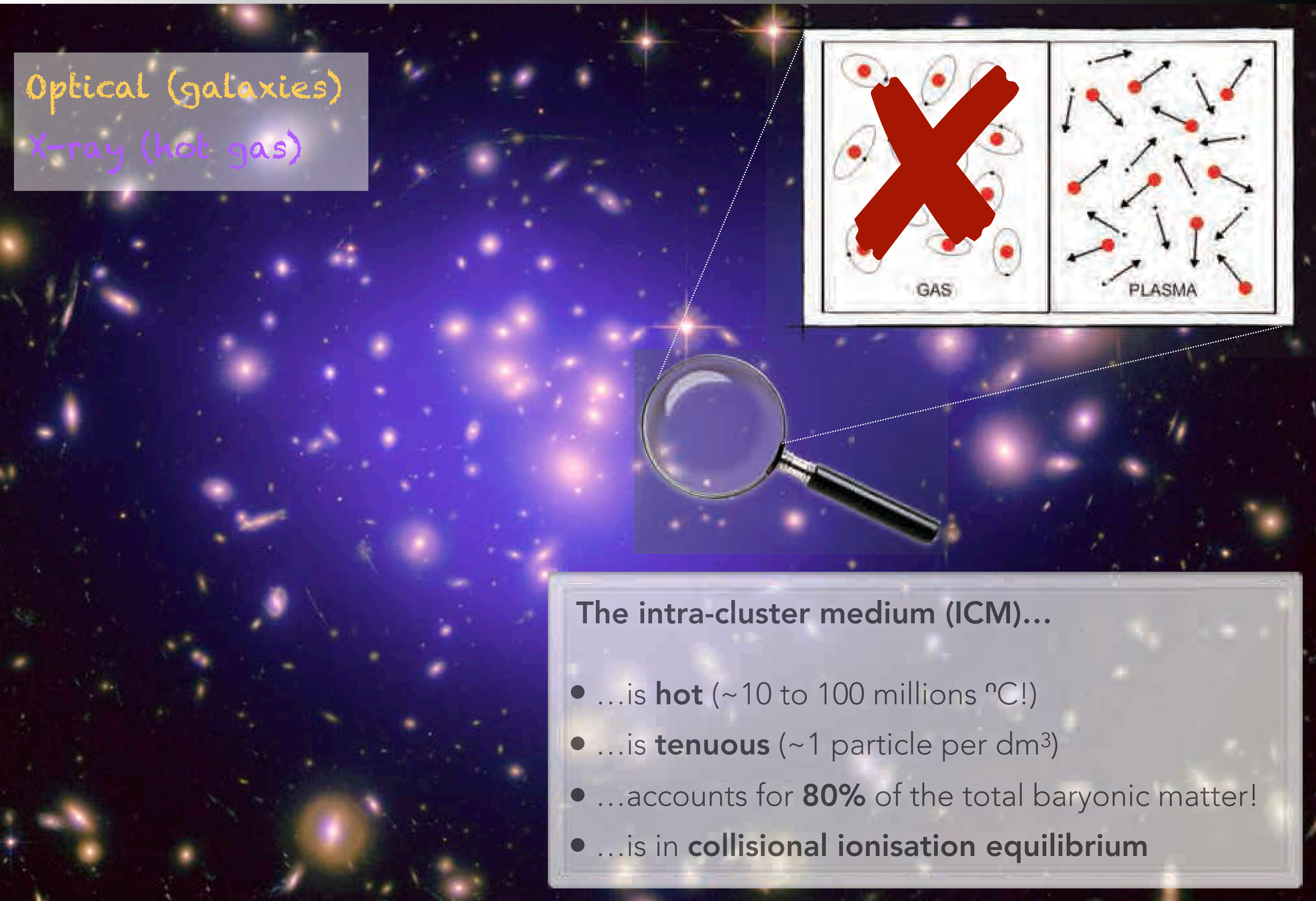
We are all made of stars/supernovae!

Galaxy clusters and the intra-cluster medium

Galaxy clusters and the intra-cluster medium



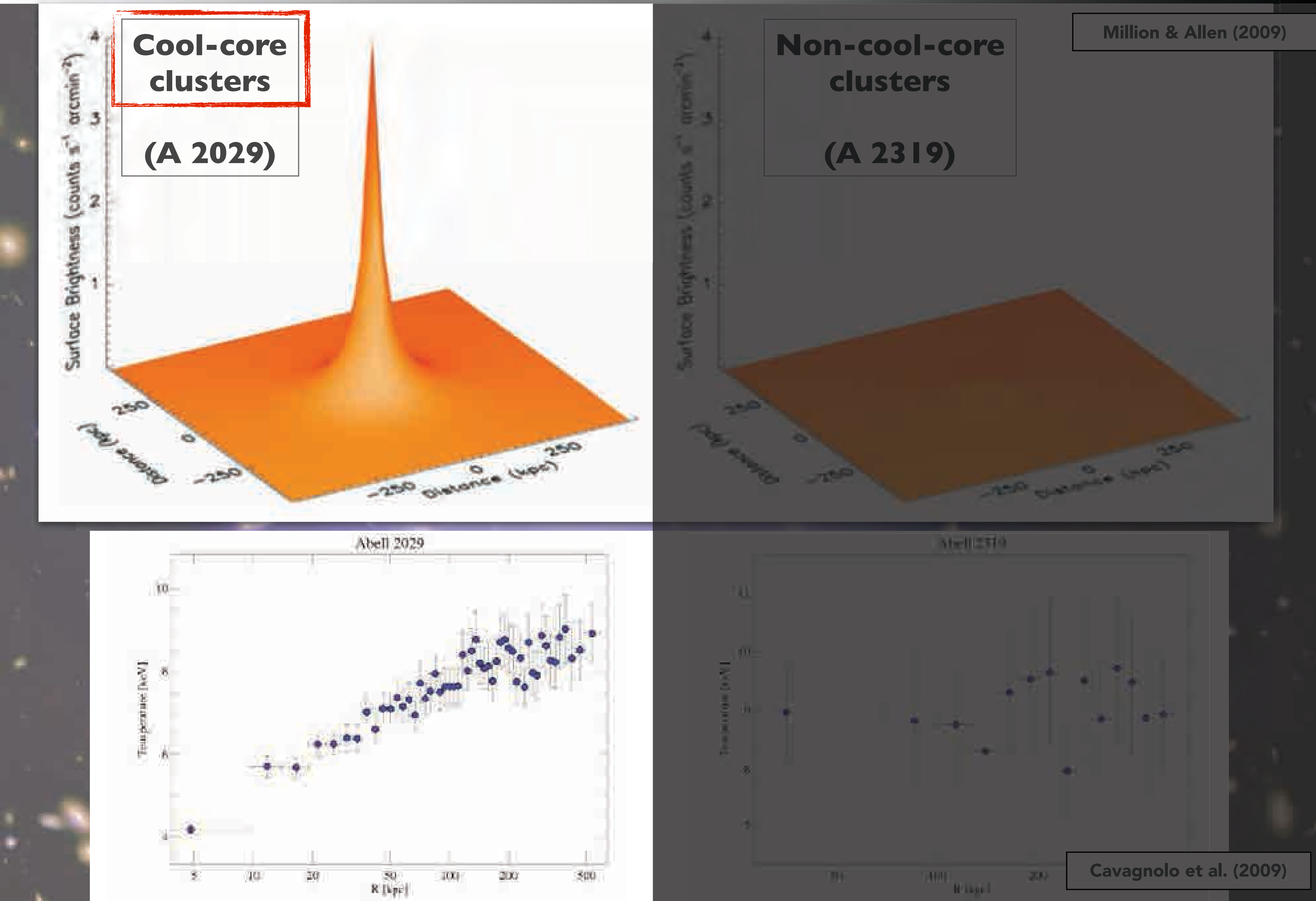
Galaxy clusters and the intra-cluster medium



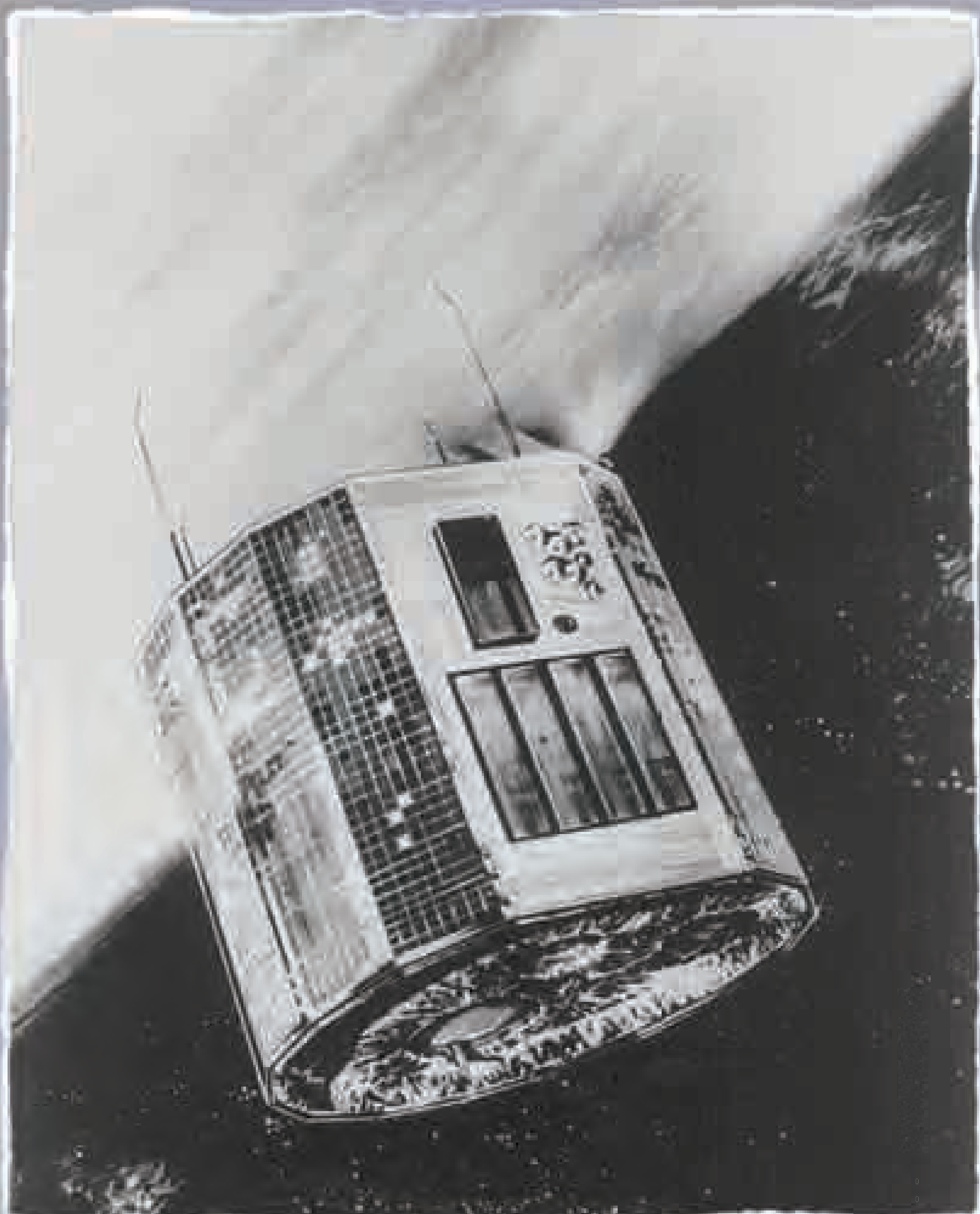
The intra-cluster medium (ICM)…

- …is **hot** (~10 to 100 millions ºC!)
- …is **tenuous** (~1 particle per dm^3)
- …accounts for **80%** of the total baryonic matter!
- …is in **collisional ionisation equilibrium**

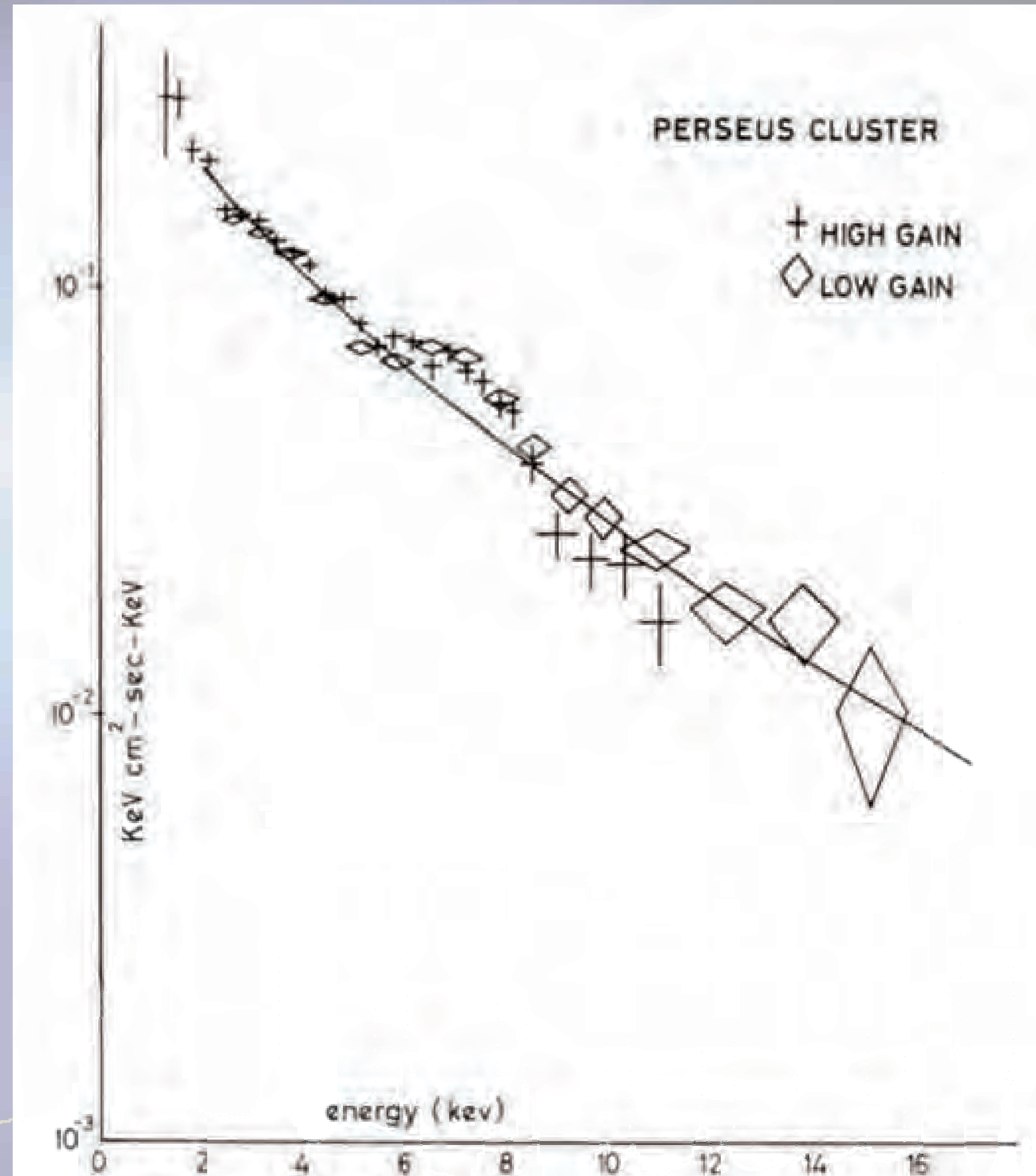
Cool-core and non-cool-core clusters



The intra-cluster medium contains metals!



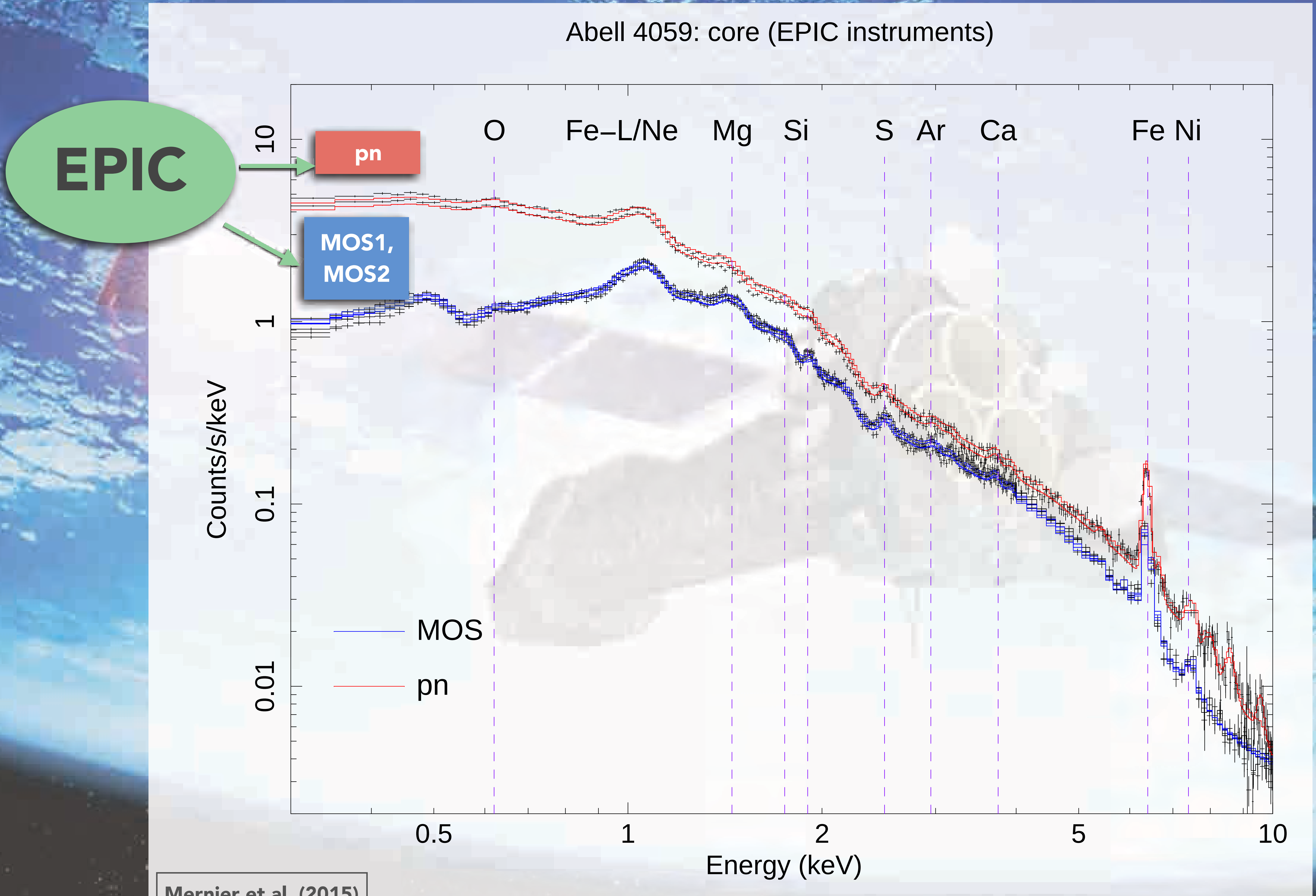
Ariel V



Mitchell et al. (1976)

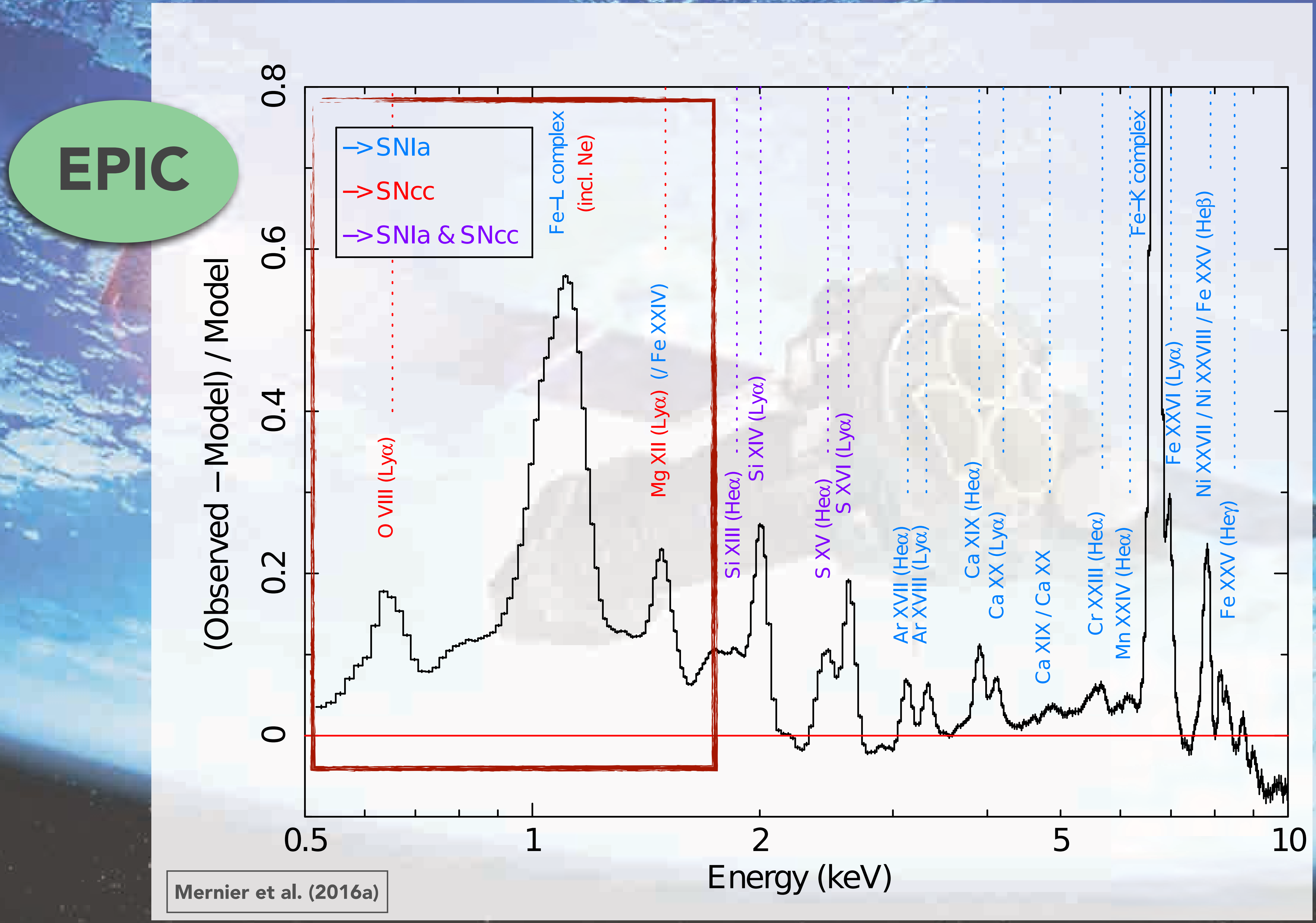
XMM-Newton

XMM-Newton



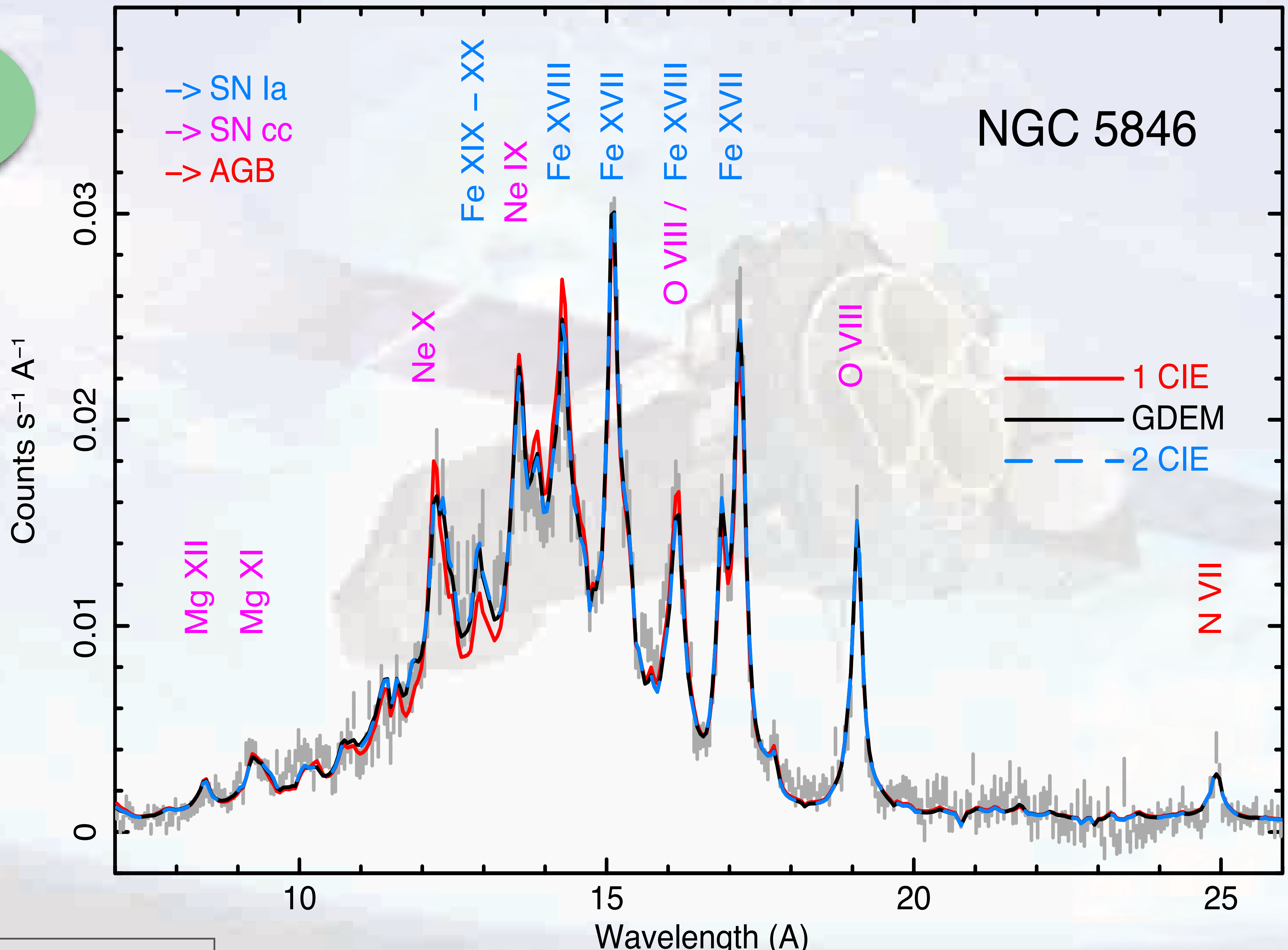
Mernier et al. (2015)

XMM-Newton


EPIC
->SNIa
->SNcc
->SNIa & SNcc
(Observed −Model) / Model
Energy (keV)
0.5
1
2
5
10
0
0.2
0.4
0.6
0.8
O VIII (Lyα)
Fe–L complex
(incl. Ne)
Mg XII (Lyα) (/ Fe XXIV)
Si XIII (Heα)
Si XIV (Lyα)
S XV (Heα)
S XVI (Lyα)
Ar XVII (Heα)
Ar XVIII (Lyα)
Ca XIX (Heα)
Ca XX (Lyα)
Ca XIX / Ca XX
Cr XXIII (Heα)
Mn XXIV (Heα)
Fe–K complex
Fe XXVI (Lyα)
Ni XXVII / Ni XXVIII / Fe XXV (Heβ)
Fe XXV (Heγ)
Mernier et al. (2016a)

XMM-Newton

RGS



de Plaa et al. (2017)

1. What do ICM abundances tell us about stars and supernovae?

How to constrain supernovae models?

- Only a few tens of SN remnants are well known so far
- The physics of SN (remnants) is usually complicated

➡**Difficult to quantify their chemical composition from spectroscopy!**

- ☑ The hot ***intra-cluster medium*** (ICM) is rich in metals!
- ☑ These metals = integrated yields from billions of SNe over Gyrs
- ☑ The ICM is in collisional ionisation equilibrium

➡**Equivalent width** of the lines ⇒ **abundances** in the ICM

CHEERS!

CHEERS stands for:
***CHE**mical **E**nrichment **R**gs **S**ample*

PI: Jelle de Plaa

- **Cool-core** galaxy clusters, groups & ellipticals
- O VIII line in RGS: > 5σ
- Nearby (z < 0.1)
- New deep observations of 11 objects (1.6 Ms)
- + archival (public) data

➡ 44 objects

➡ ~4.5 Ms
of *XMM-Newton* total net exposure

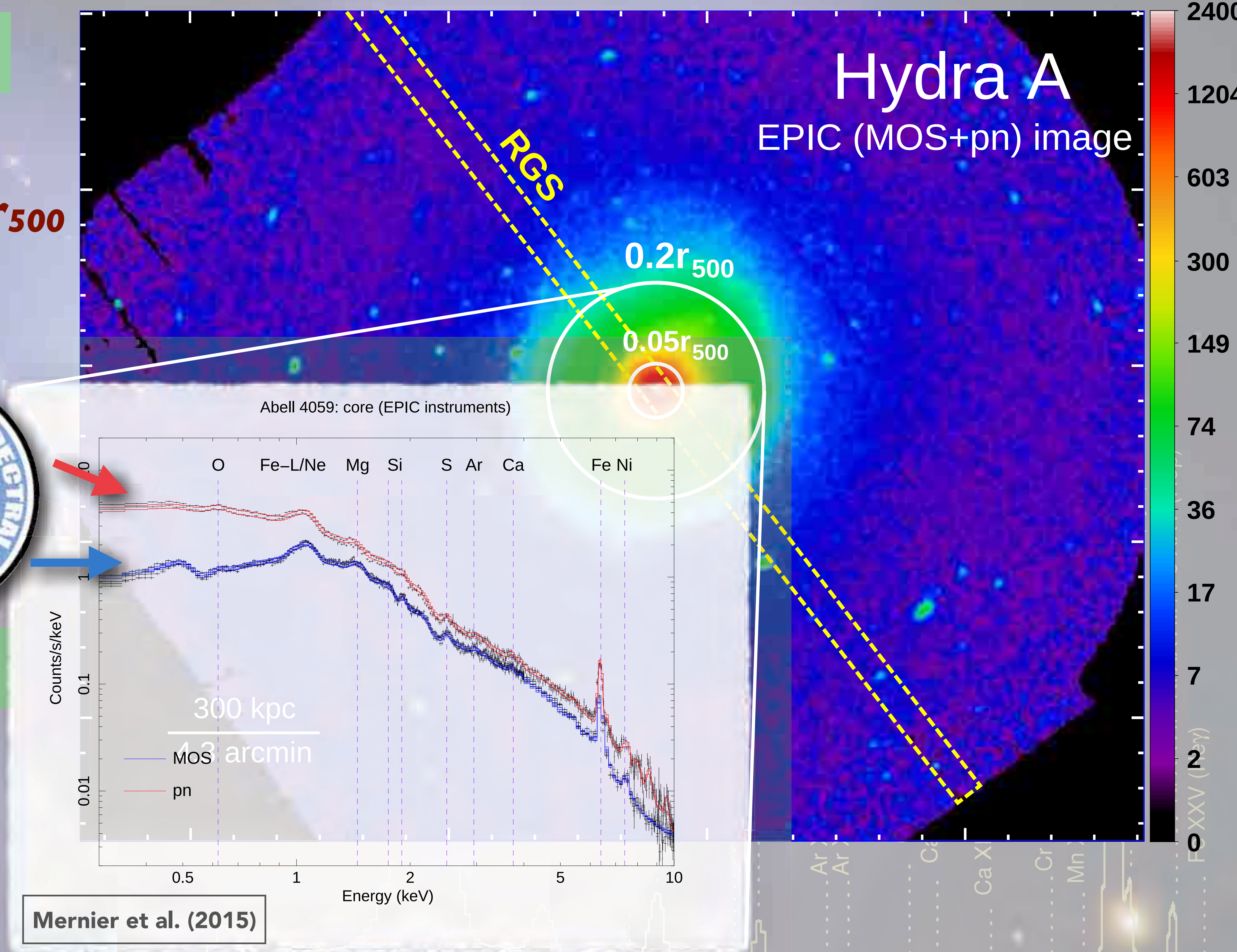
Strategy (CHEERS sample)

EPIC

- Clusters (>1.7 keV):
  0.2 r_{500} & 0.05 r_{500}
- Groups (< 1.7 keV):
  0.05 r_{500}

RGS

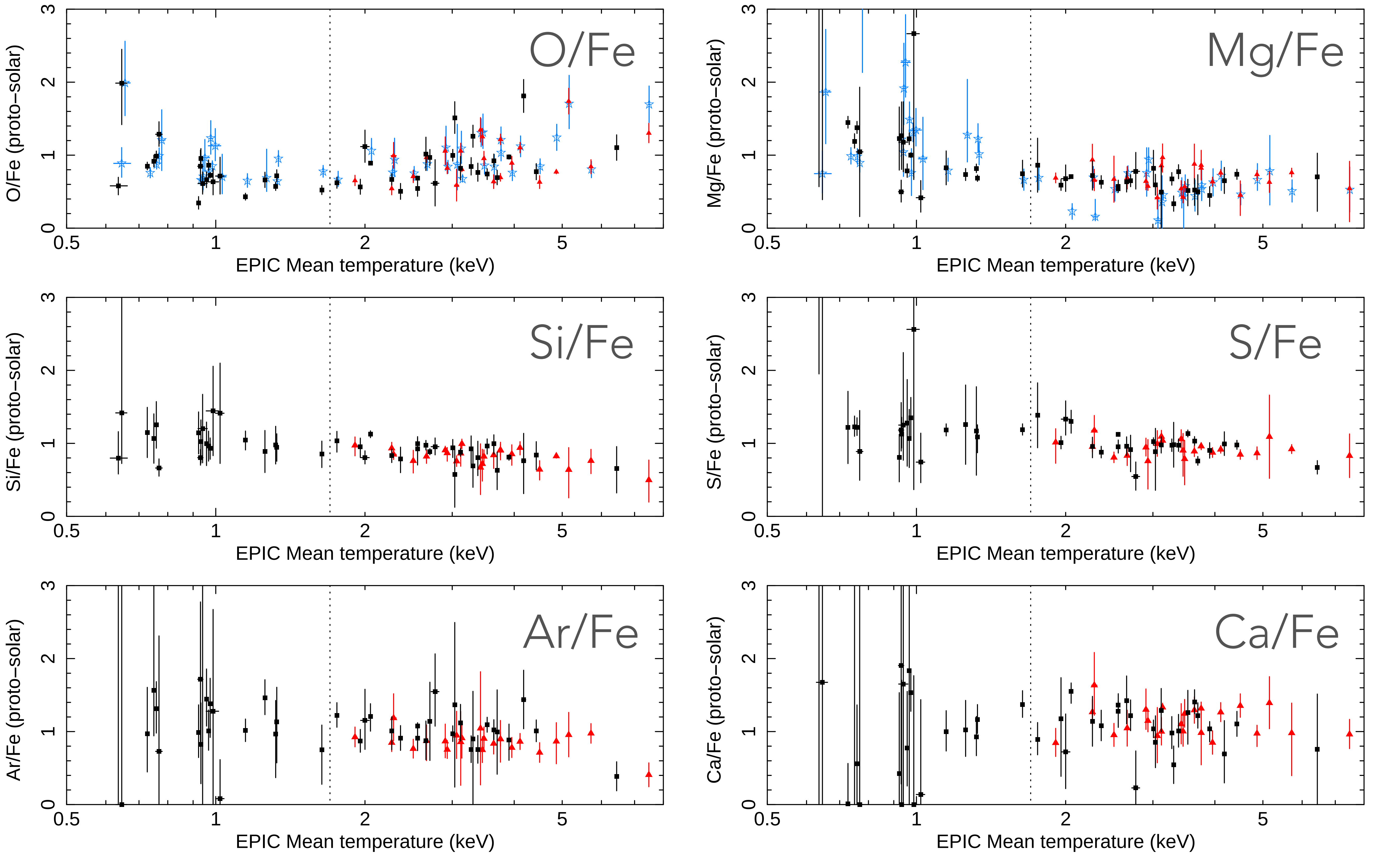
- **0.8 arcmin**



Mernier et al. (2015)

r_{500}: radius within which mass density = 500 x (critical density of the Universe)

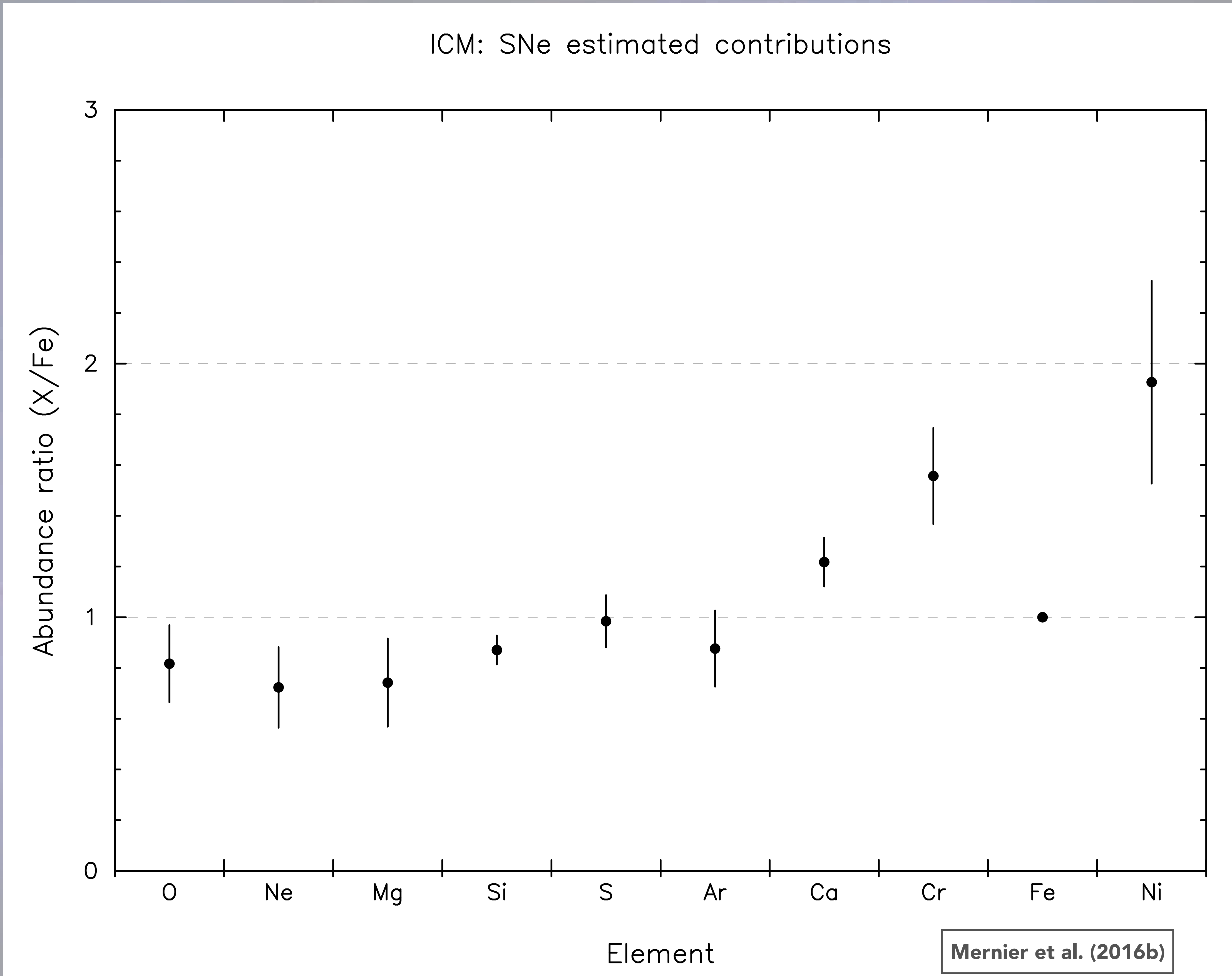
Central abundance ratios



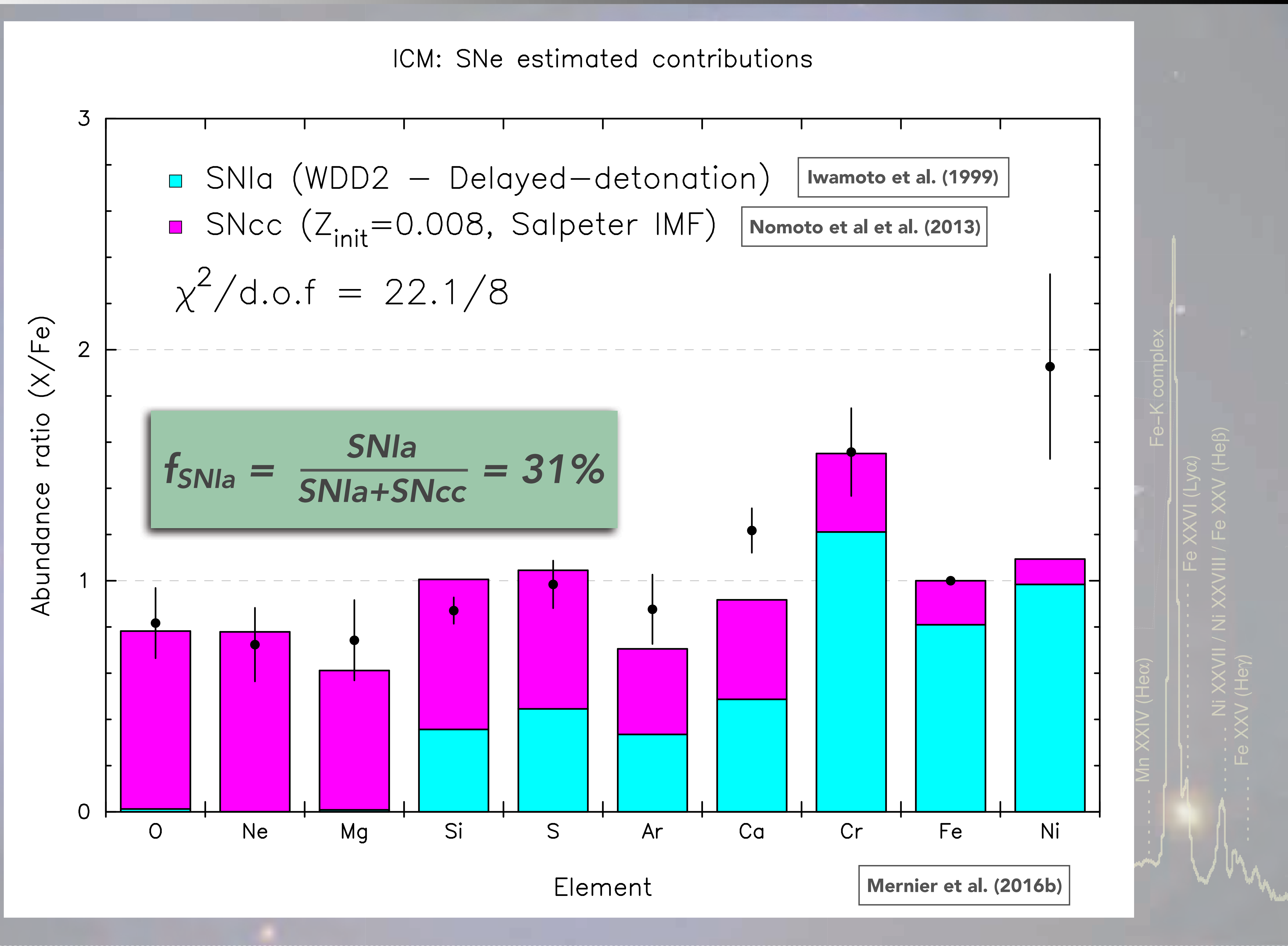
EPIC (0.2r_{500}) EPIC (0.05r_{500}) RGS (0.8′)

Mernier et al. (2016a) (see also de Plaa et al. 2017)

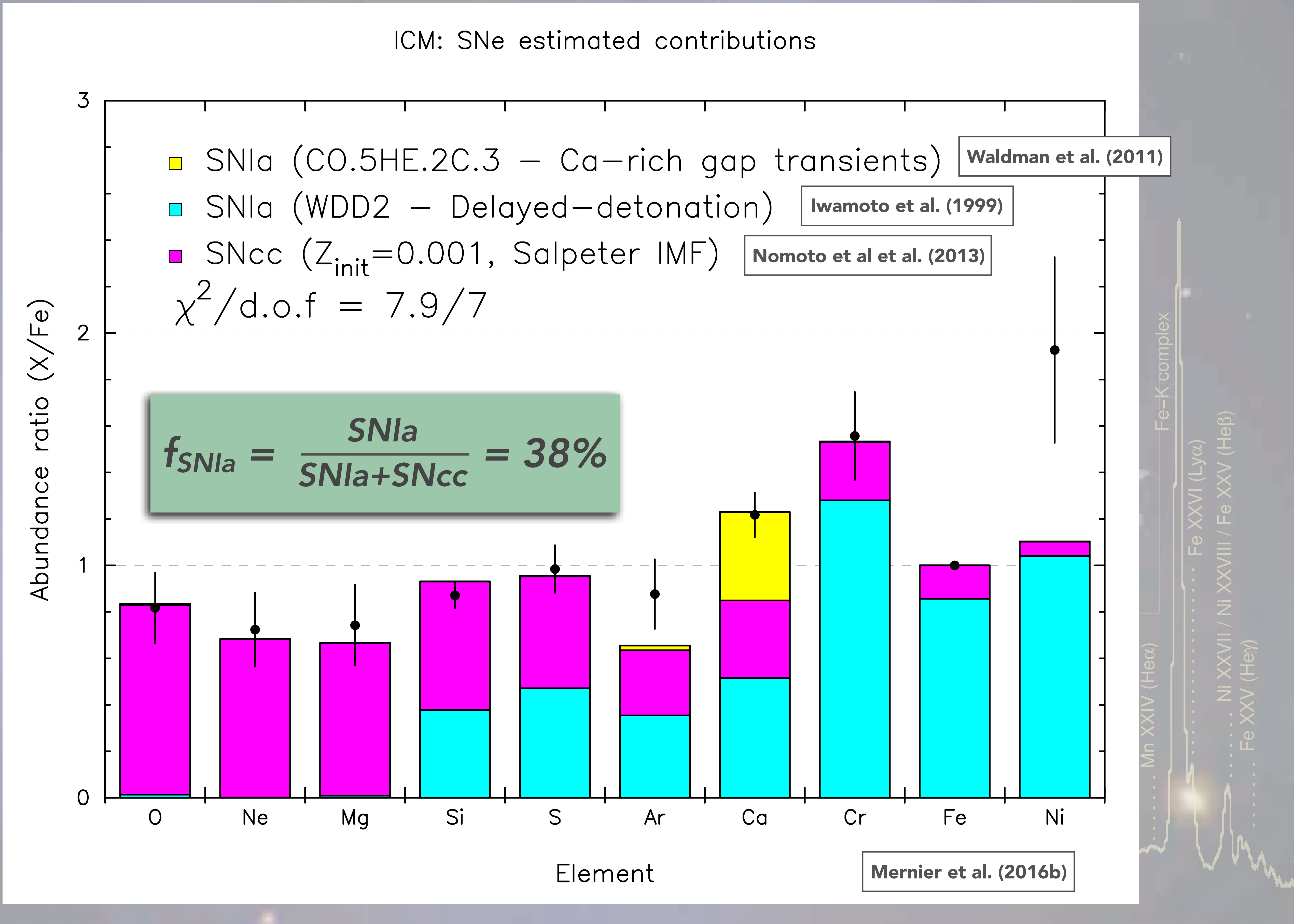
Average ICM abundance pattern



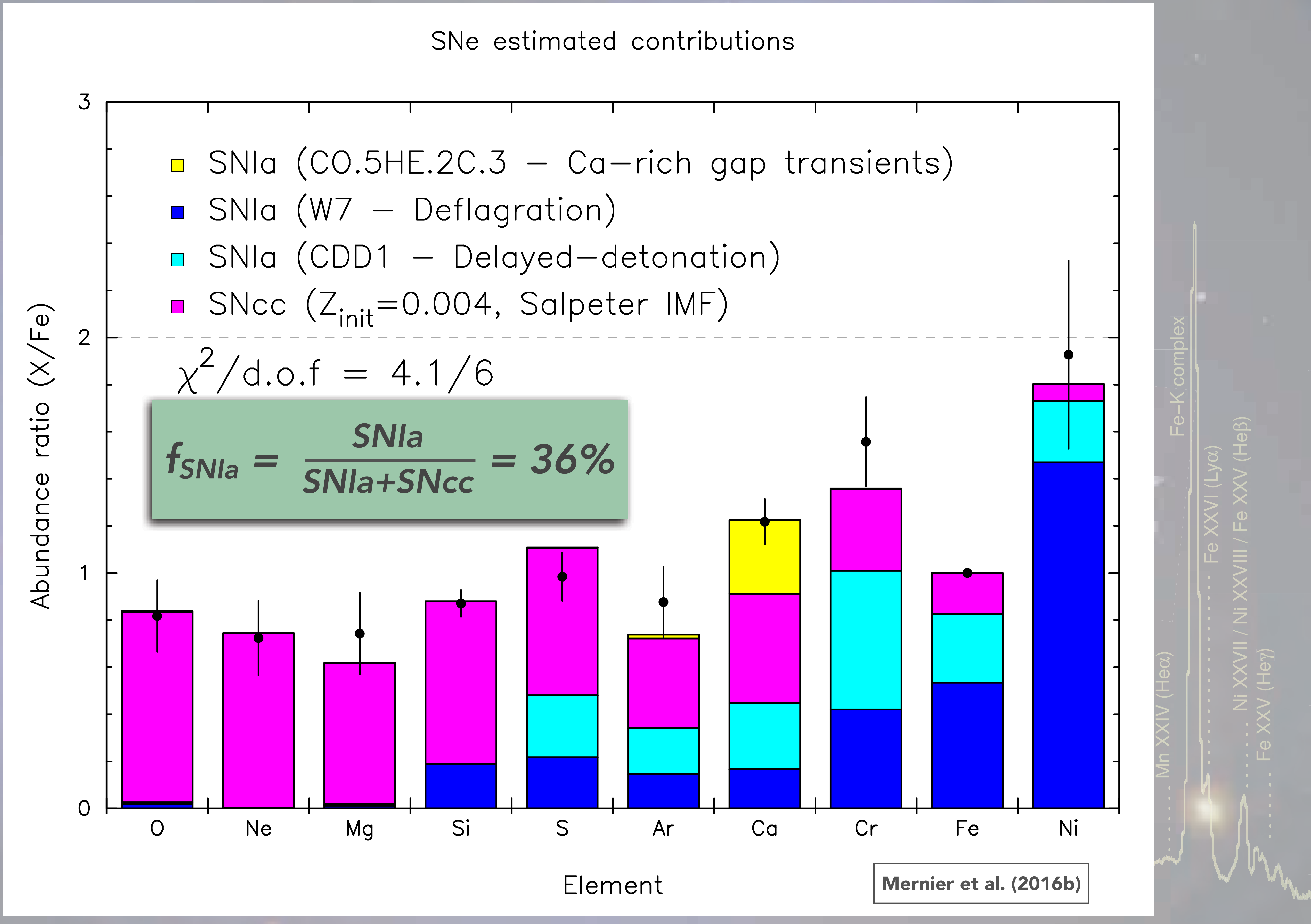
Average ICM abundance pattern



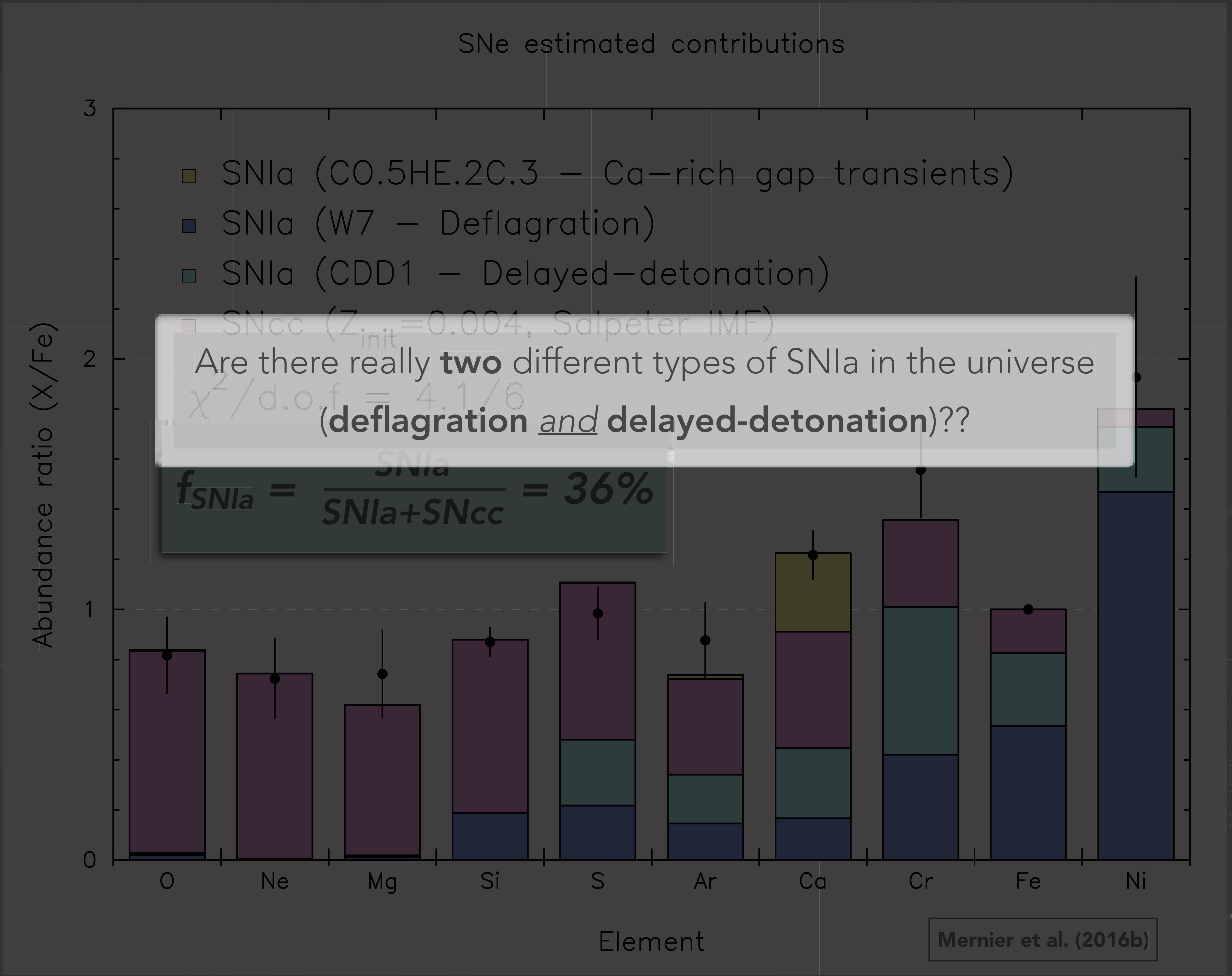
Average ICM abundance pattern



Average ICM abundance pattern



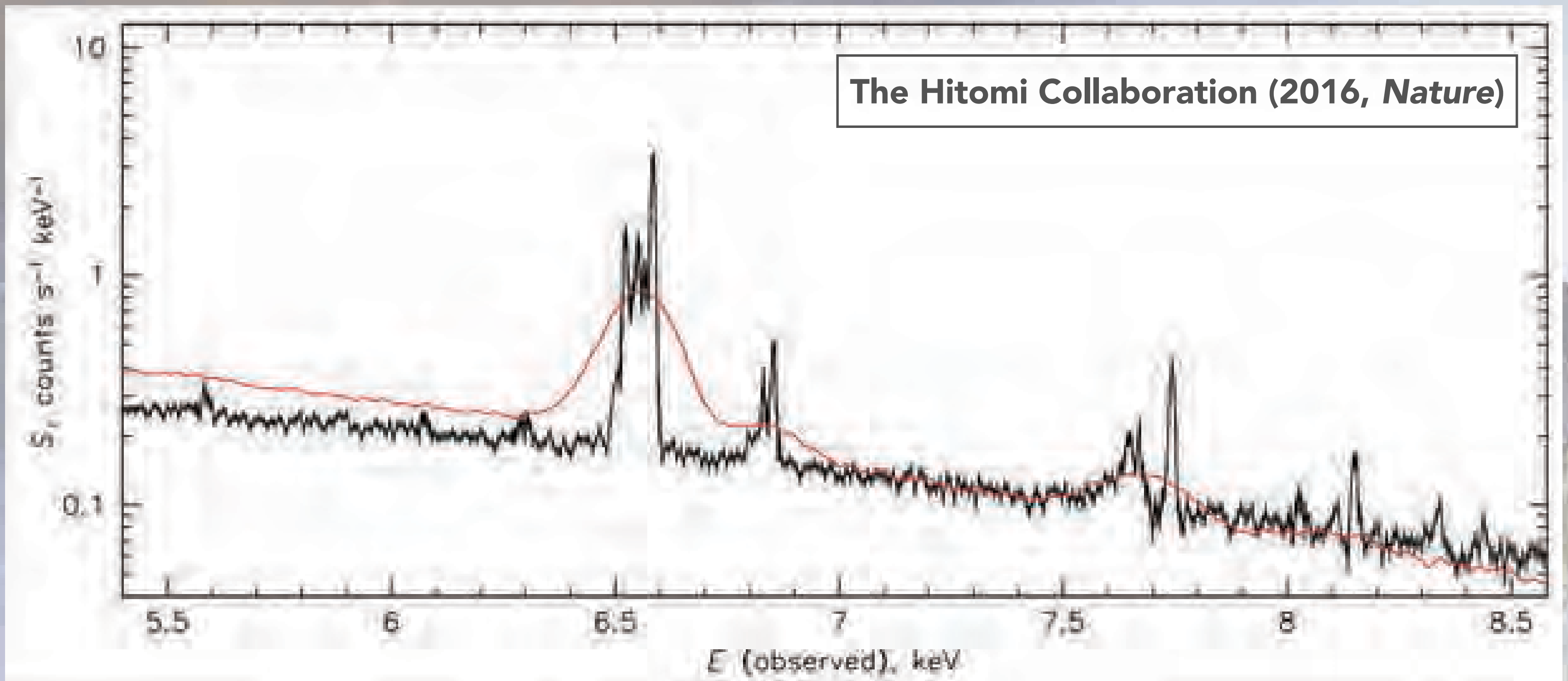
Average ICM abundance pattern

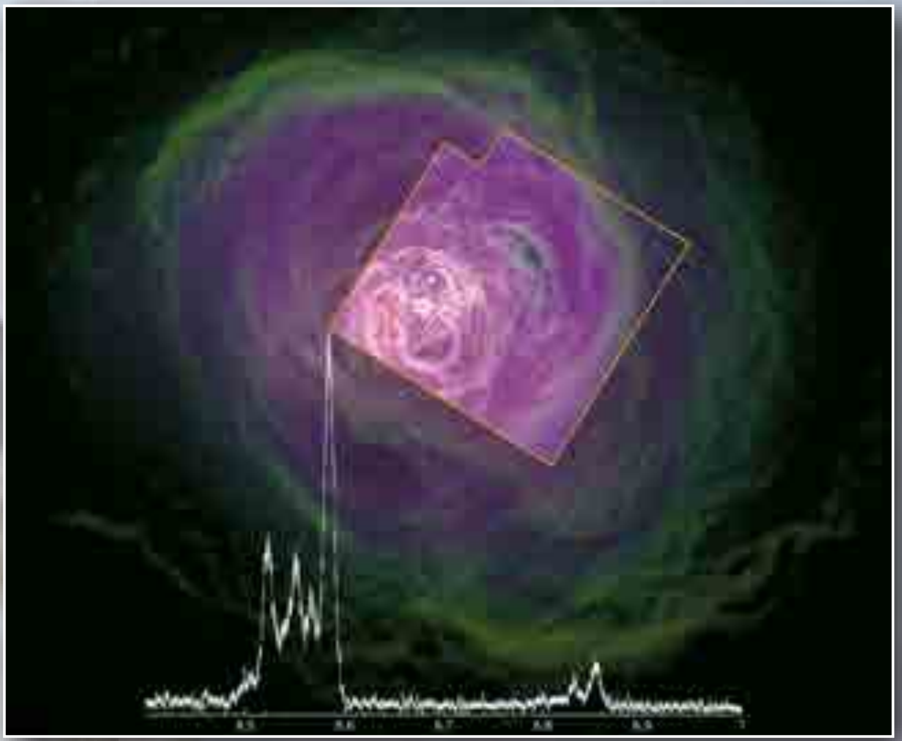


Are there really **two** different types of SNIa in the universe (**deflagration** *and* **delayed-detonation**)??

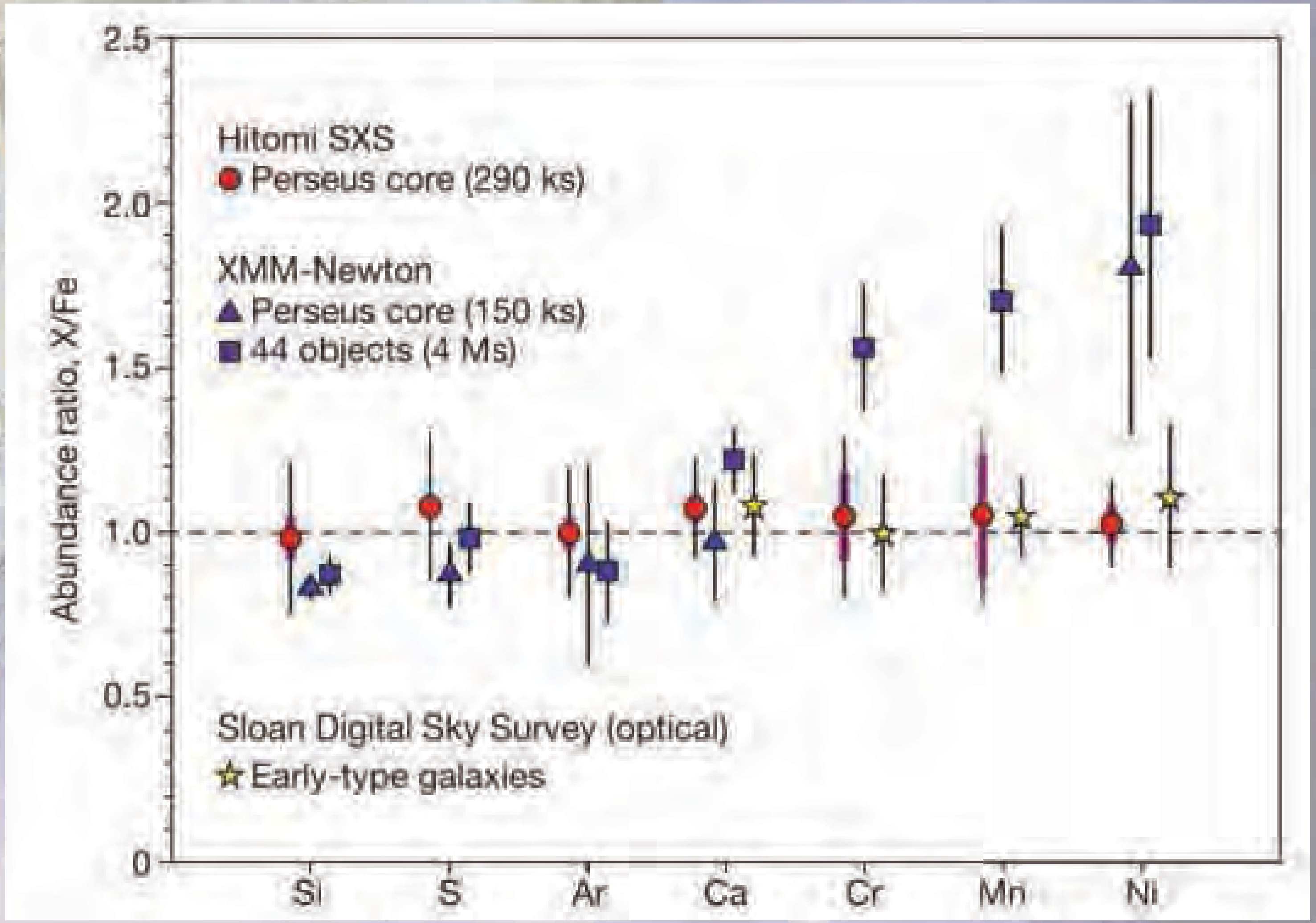
Hitomi (February 2016 - March 2016)

Hitomi (February 2016 - March 2016)





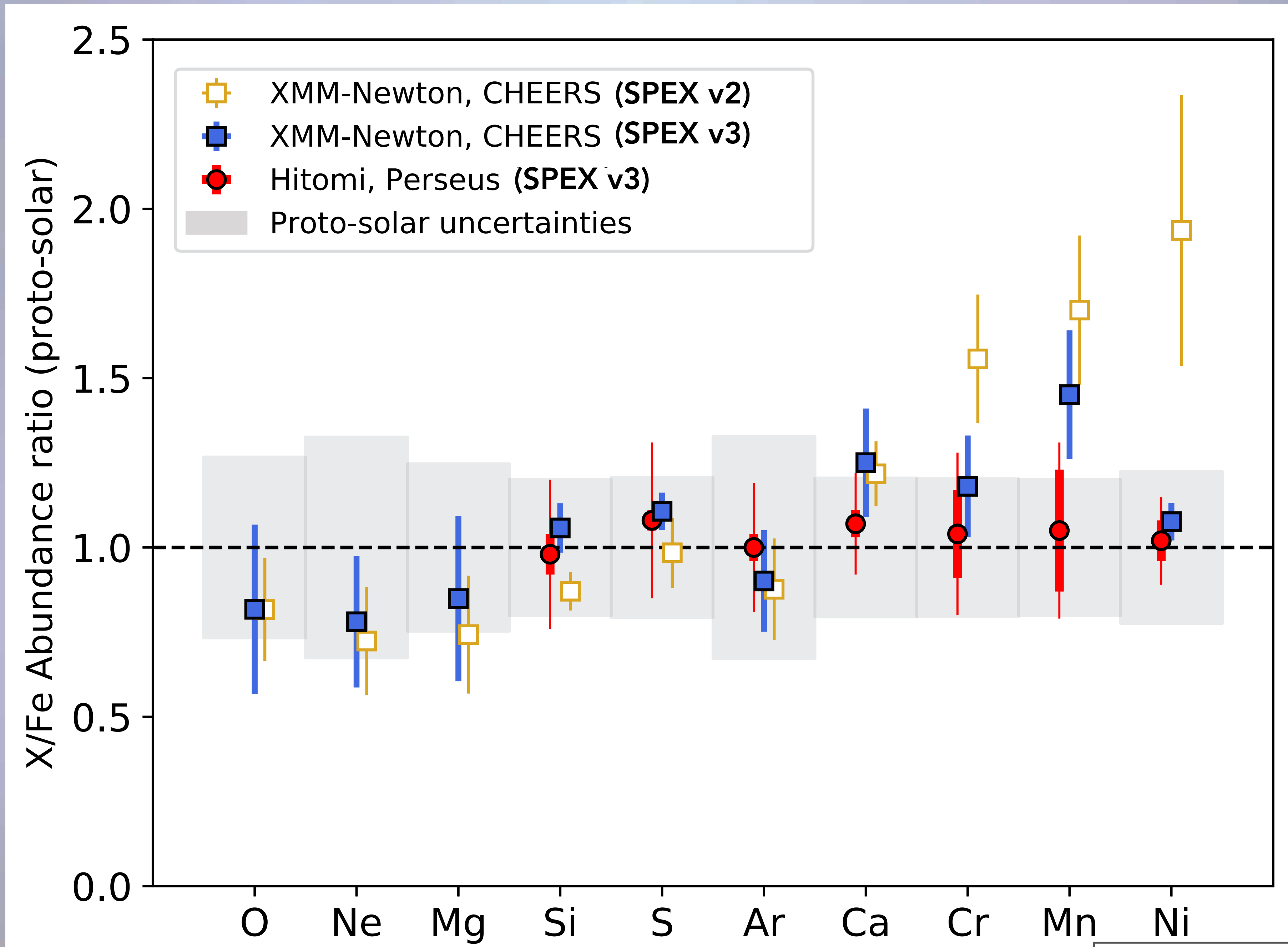
- New observatory/instrument
  - CCD ➔ ***micro-calorimeter***
- New spectral fitting code
  - SPEX v2 ➔ ***SPEX v3***



The Hitomi Collaboration (2017, *Nature*)

From SPEX v2 to SPEX v3

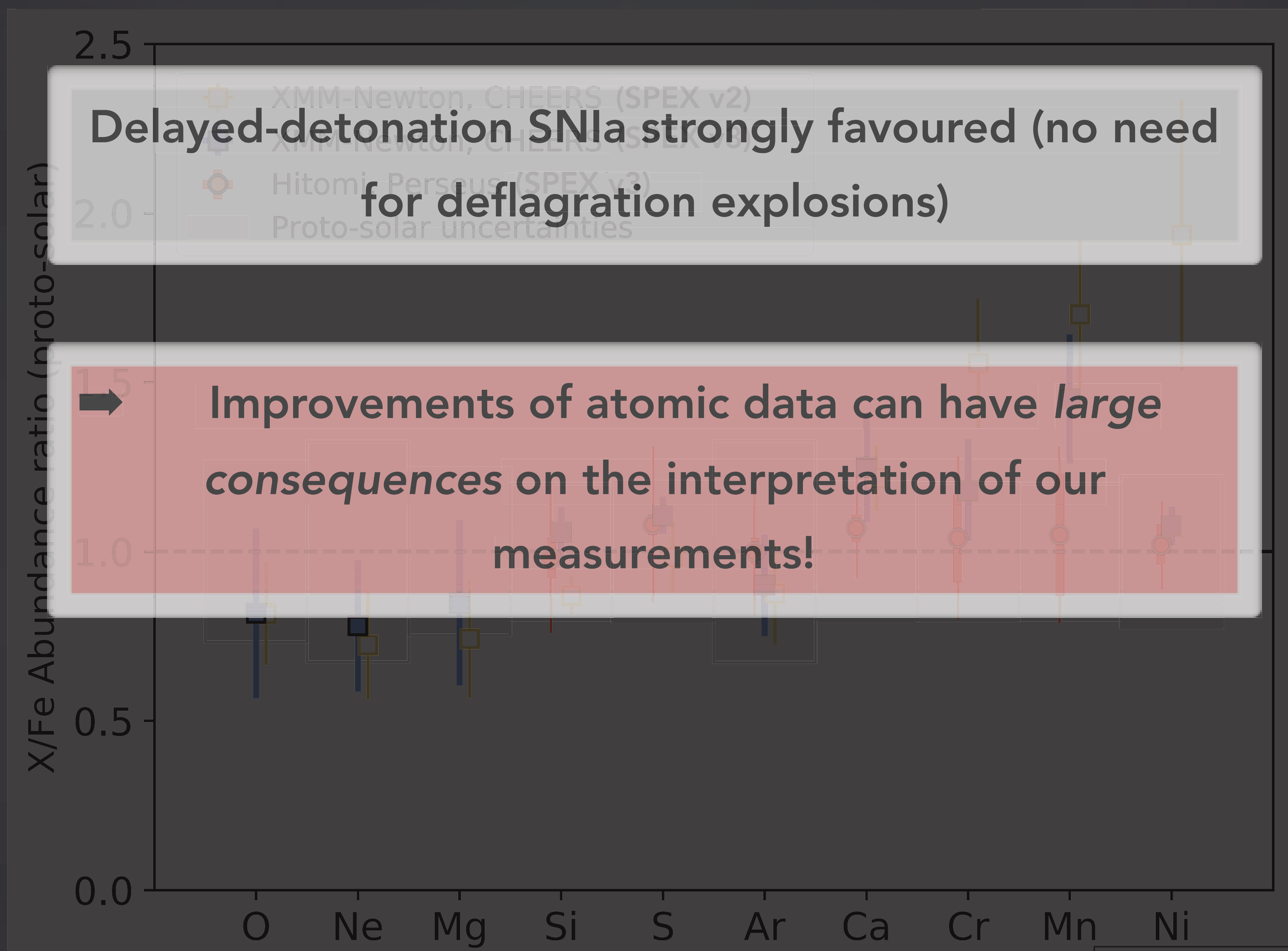
- When using the new spectral fitting code (**SPEX v3**) on our XMM-Newton data…
  - **All** abundance ratios are consistent with being **solar**!
  - Agrees with **Hitomi** results!
  - The abundance measurements of XMM-Newton are **reliable** too!

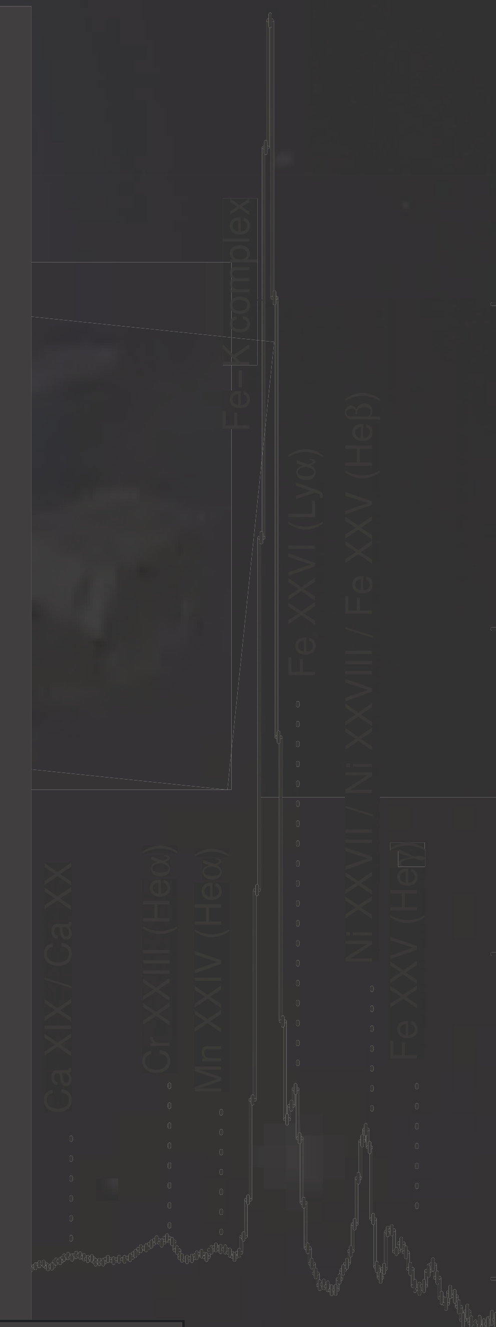


Mernier et al. (in prep.)

From SPEX v2 to SPEX v3

- When using the new spectral fitting code (**SPEX v3**) on our XMM-Newton data…
  - **All** abundance ratios are consistent with being **solar**!
  - Agrees with **Hitomi** results!
  - The abundance measurements of XMM-Newton are **reliable** too!





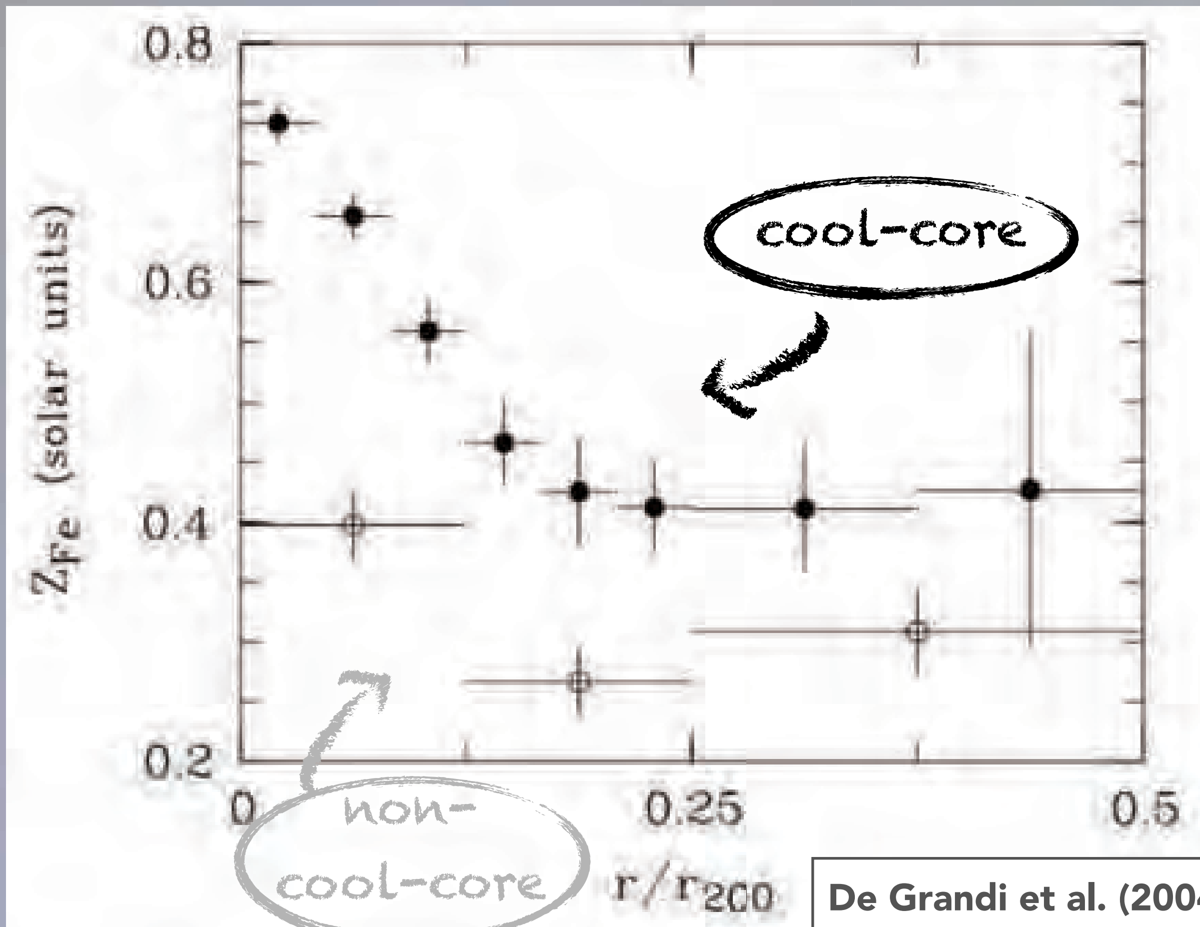
Delayed-detonation SNIa strongly favoured (no need for deflagration explosions)

➡ **Improvements of atomic data can have *large consequences* on the interpretation of our measurements!**

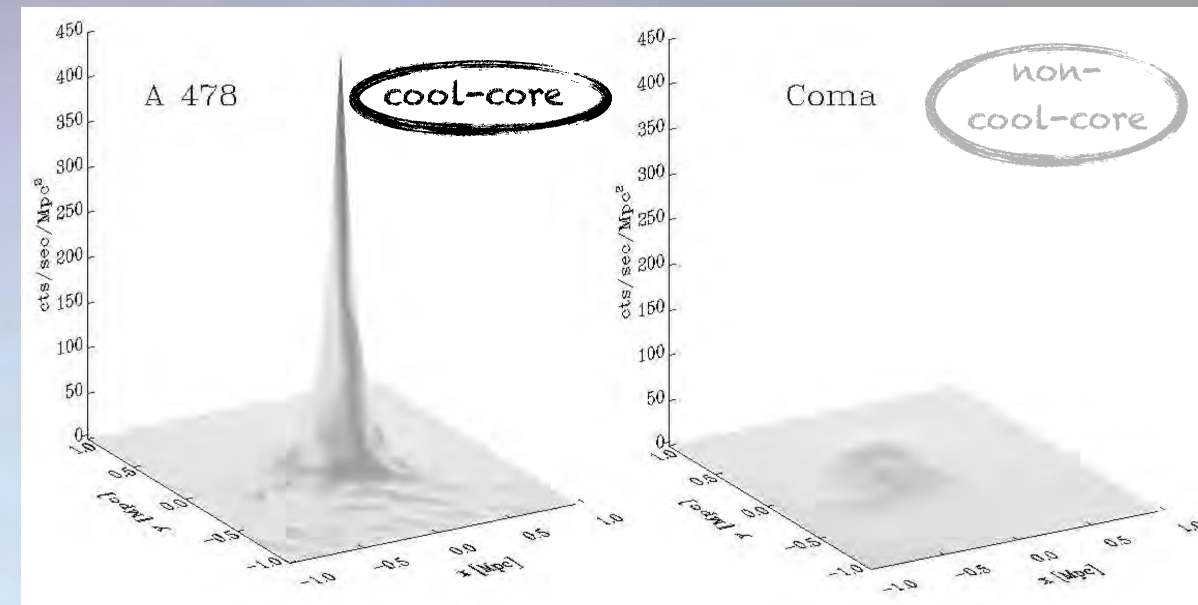
Mernier et al. (in prep.)

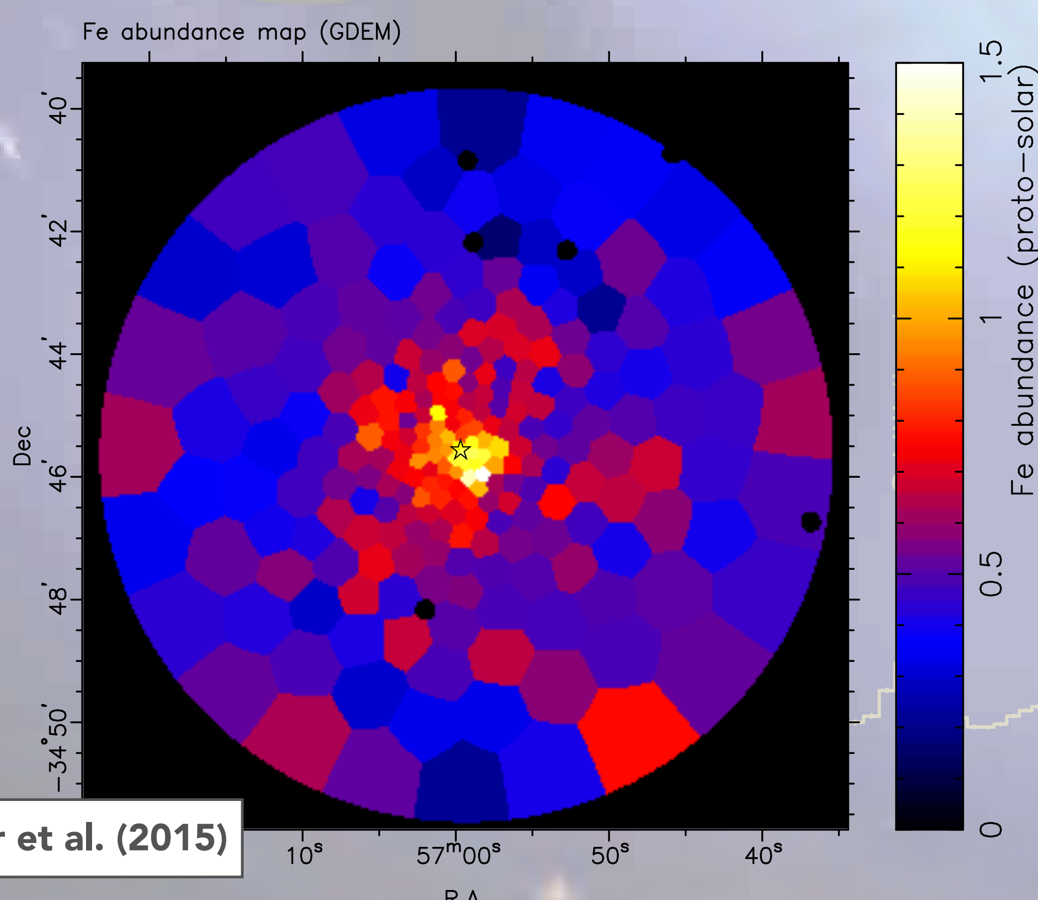
2. Where, when, and how was the intra-cluster medium enriched?

Fe (SNIa) enrichment in the ICM: core



De Grandi et al. (2004)

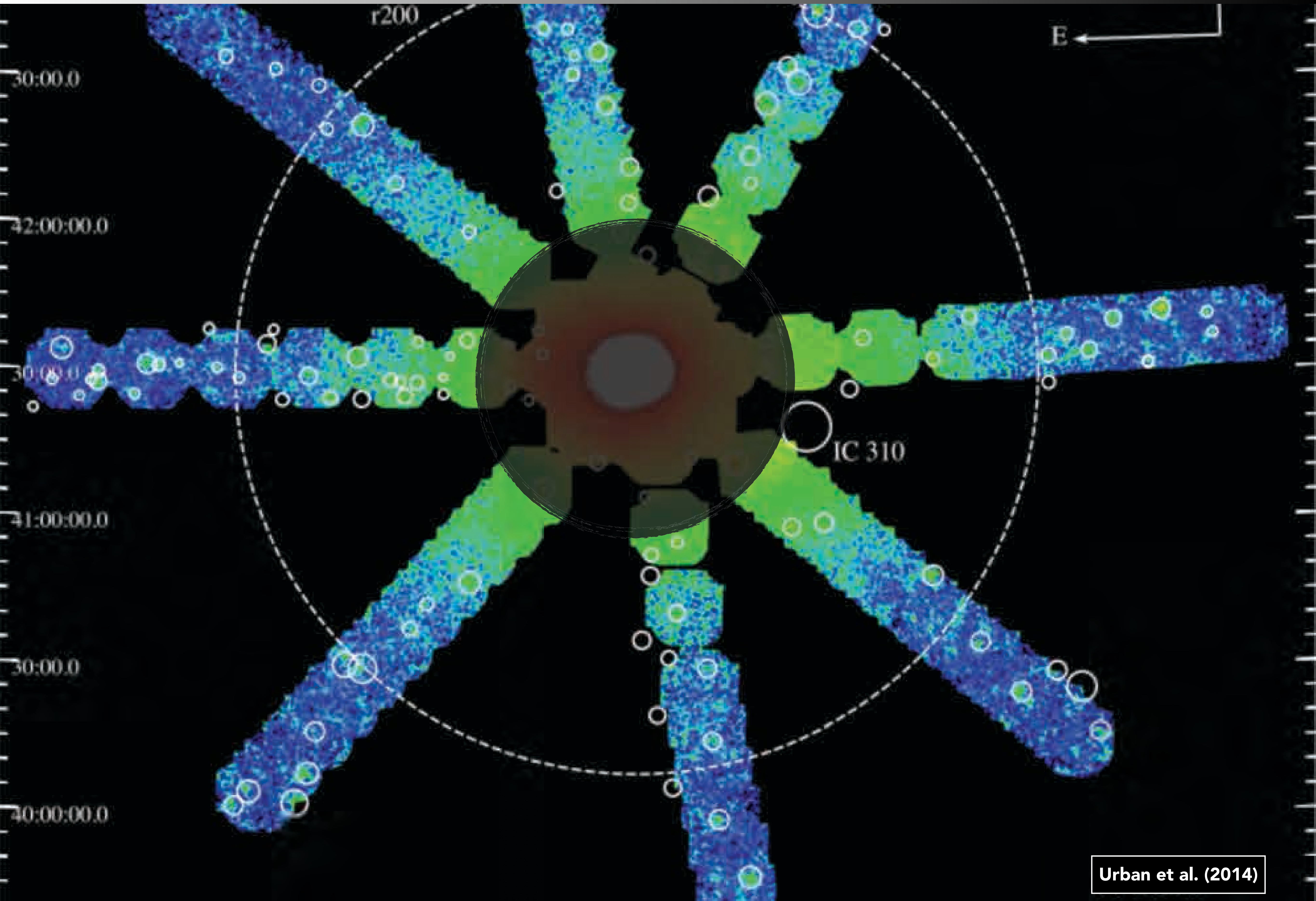




Mernier et al. (2015)

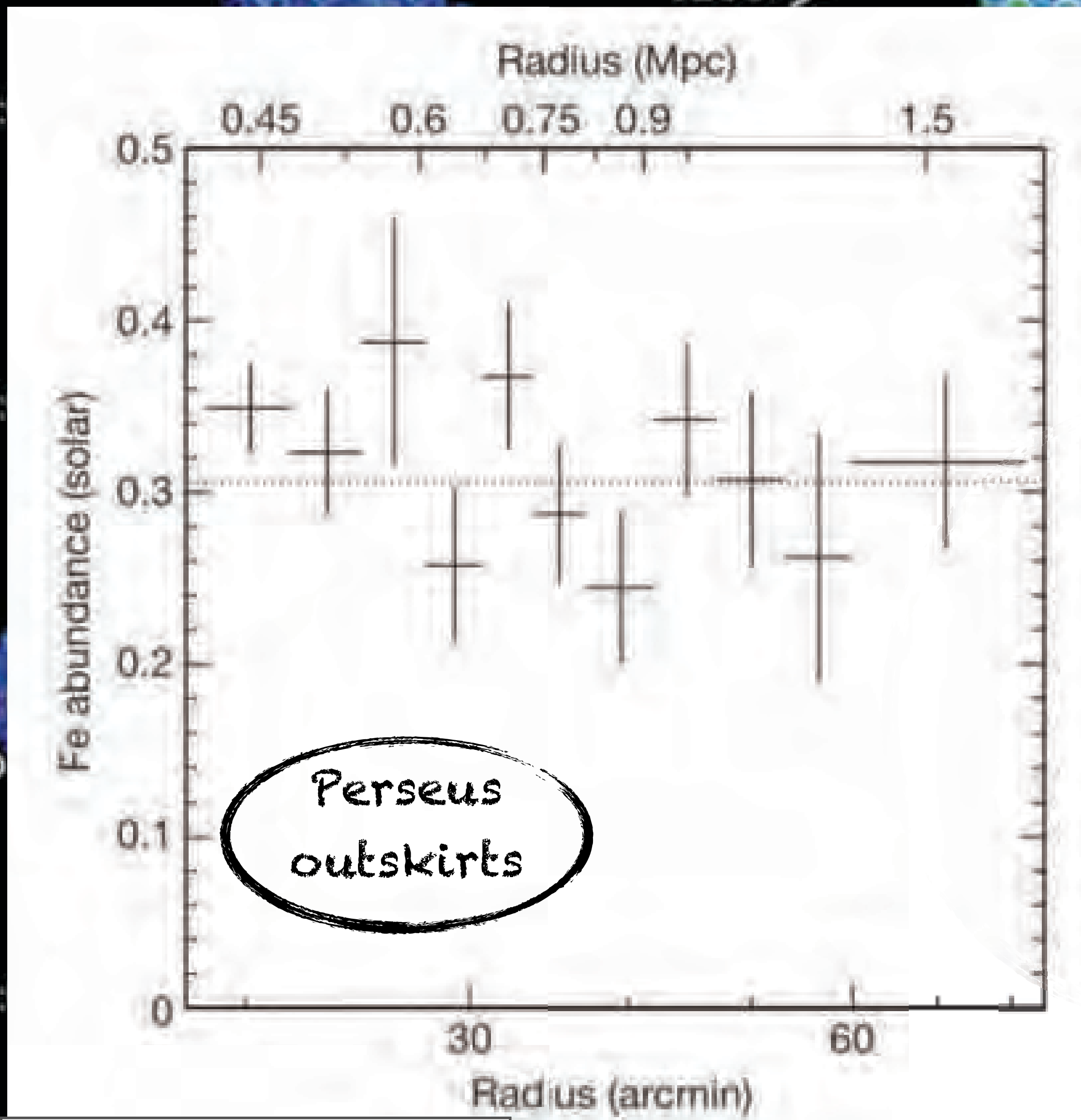
- **Cool-core** clusters ➔ Fe central peak
  - Fe mass of the peak could be entirely produced by SNIa from the (red-and-dead) brightest cluster galaxy (**BCG**)…
  - …but the Fe peak extent is larger than the BCG extent
    - ➡ **Diffusion** of metals out of the core?
- **Non-cool-core** clusters ➔ Flatter Fe distribution

Fe (SNIa) enrichment in the ICM: outskirts

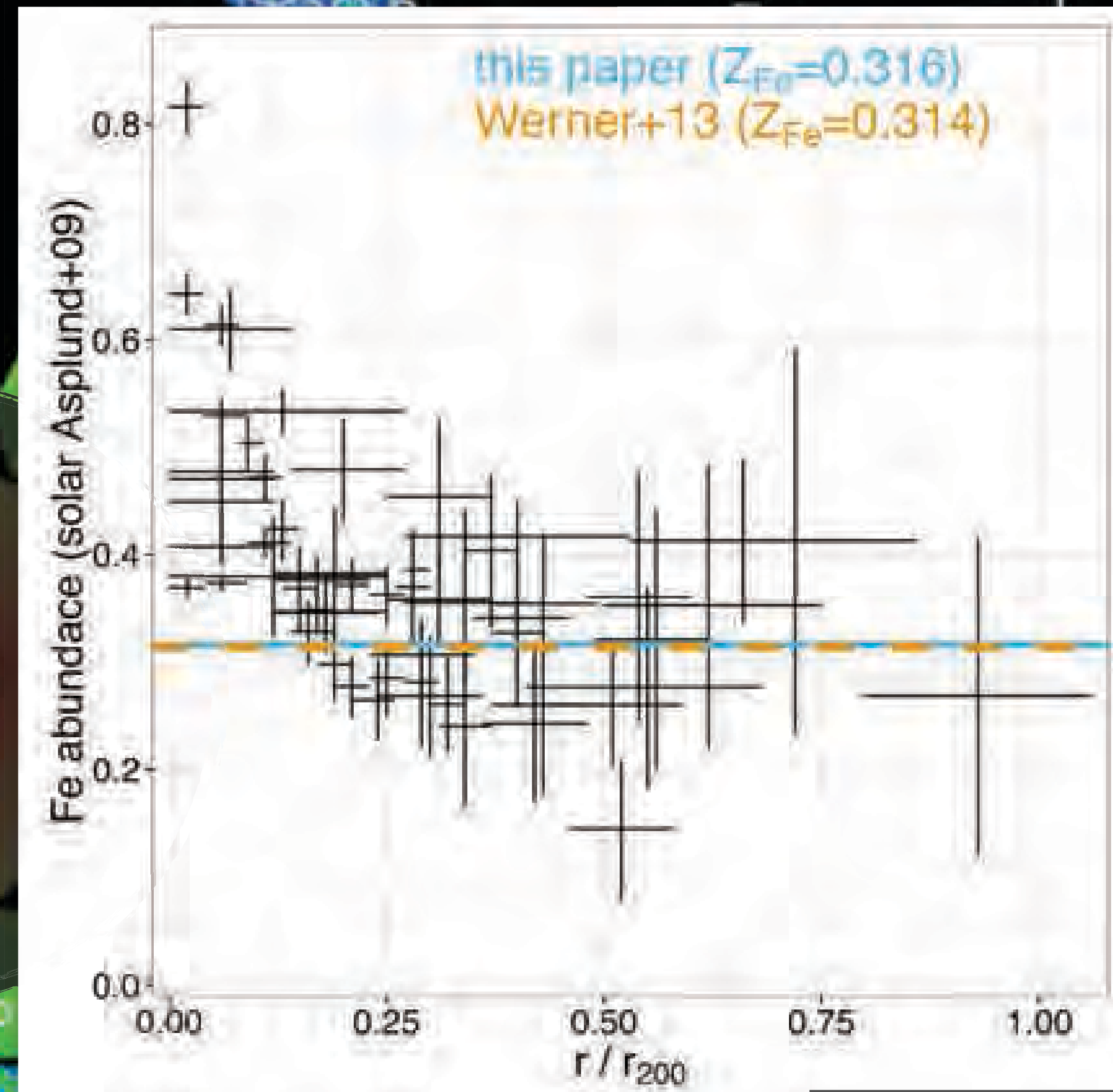


Urban et al. (2014)

Fe (SNIa) enrichment in the ICM: outskirts



Werner et al. (2013, *Nature*)



Urban et al. (2017)

Increasing evidence towards a flat Fe floor outside of the core

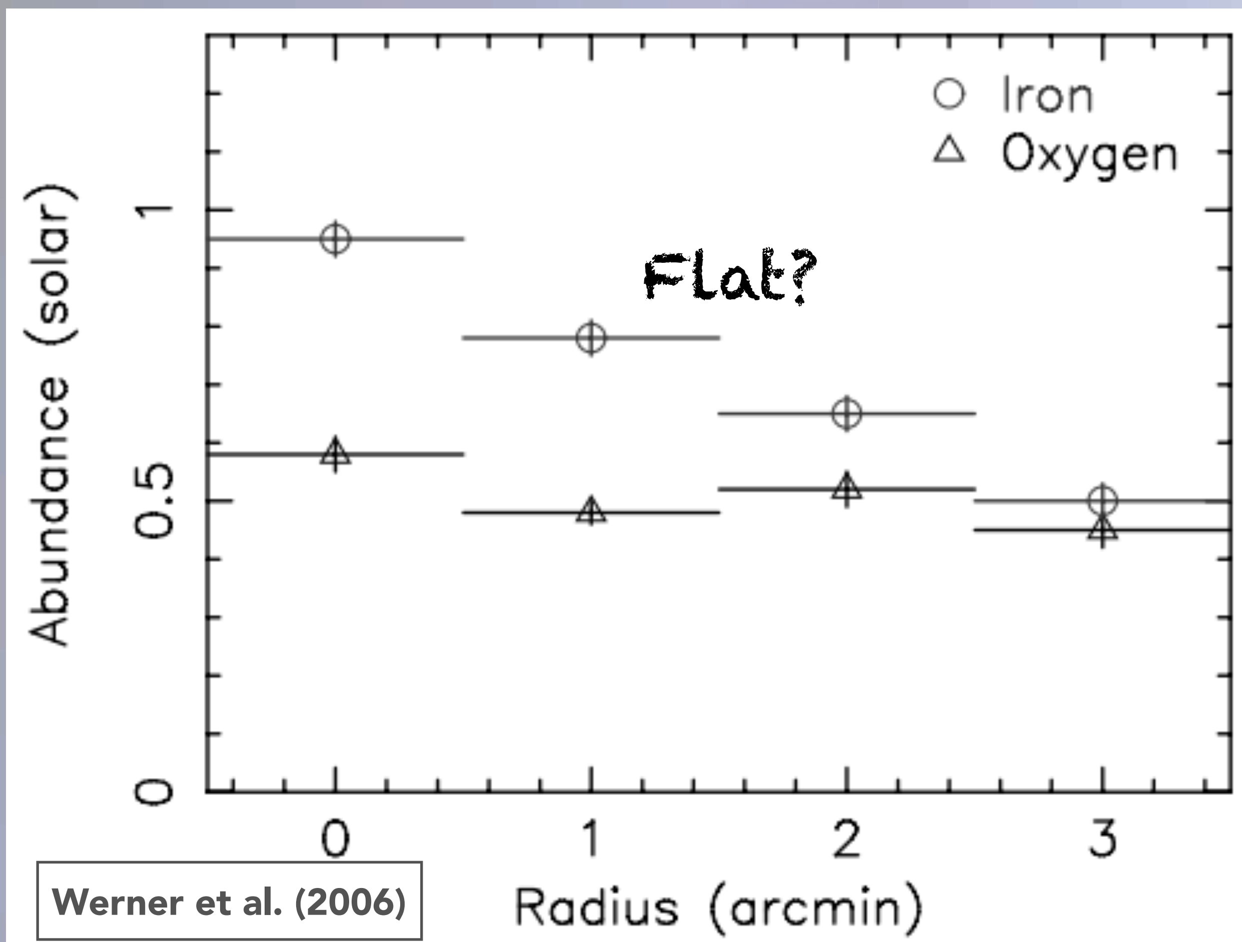
➡ **Early** epoch SNIa enrichment

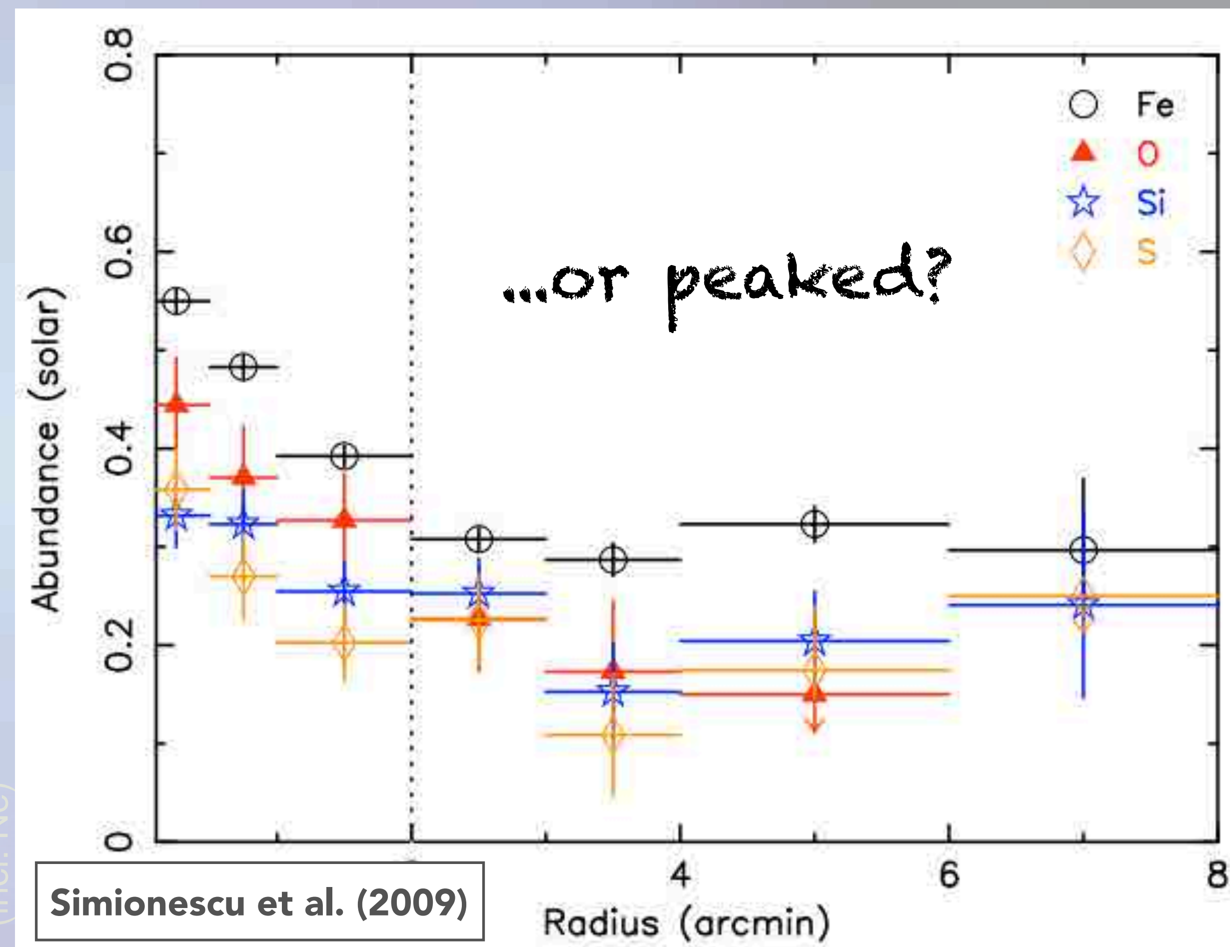
(**before** the cluster assembled, more than ~10 Gyrs ago)!

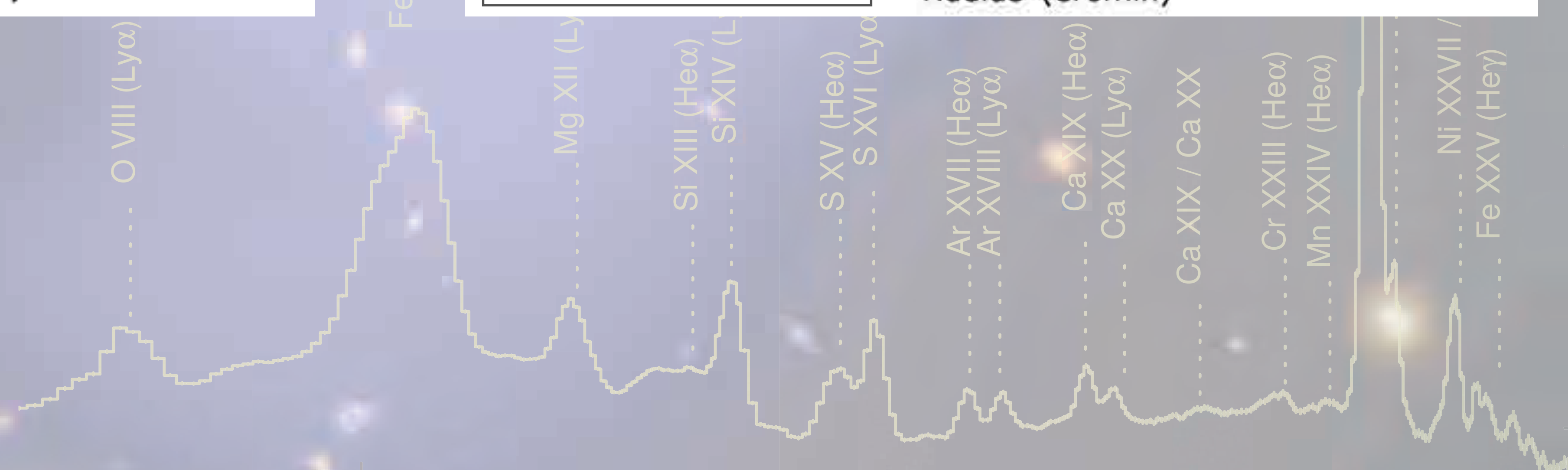
➡ Via **galactic winds** and **feedback** from their central supermassive black holes

Urban et al. (2014)

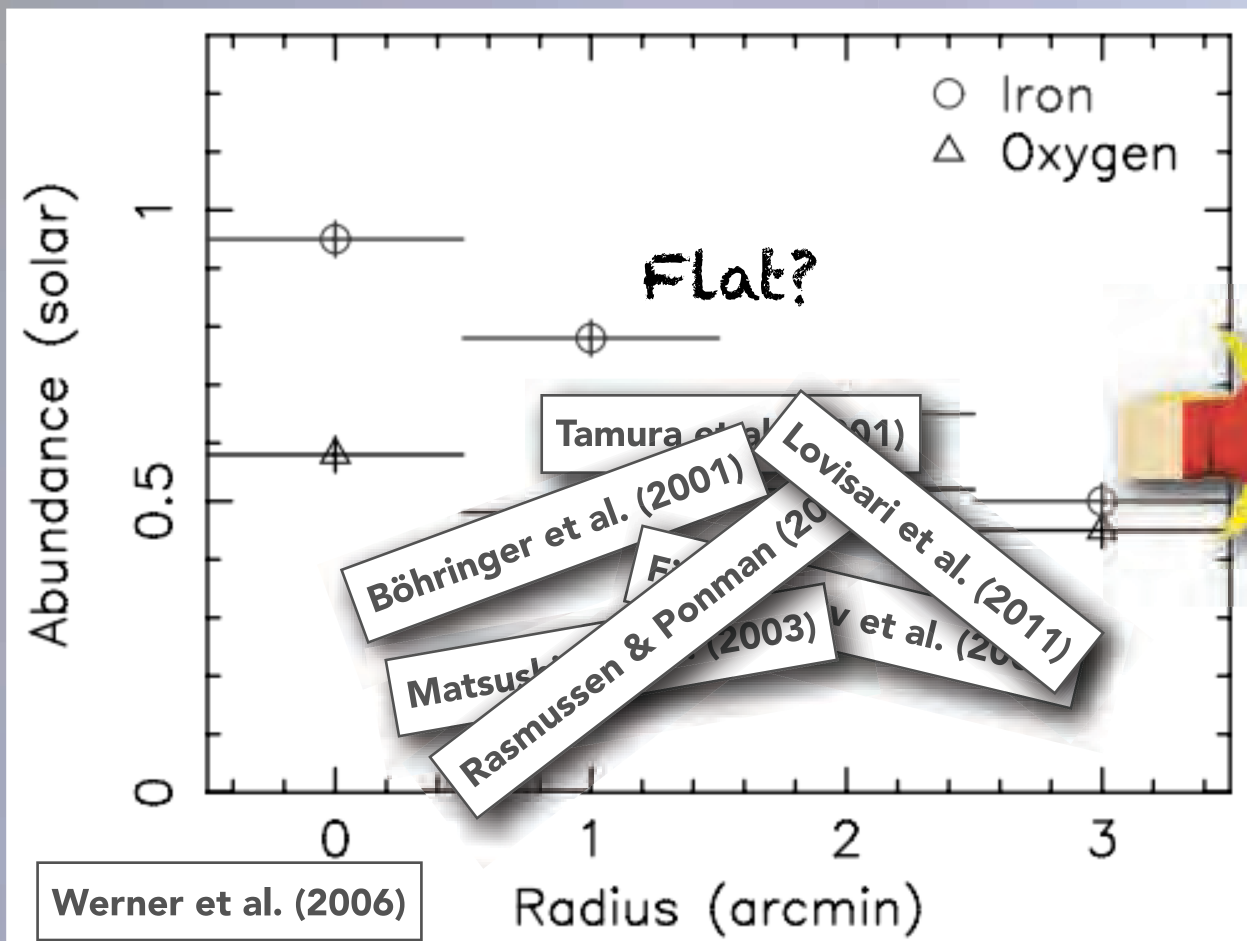
…how about other elements (SNcc products)?

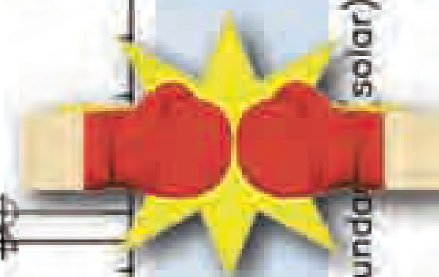


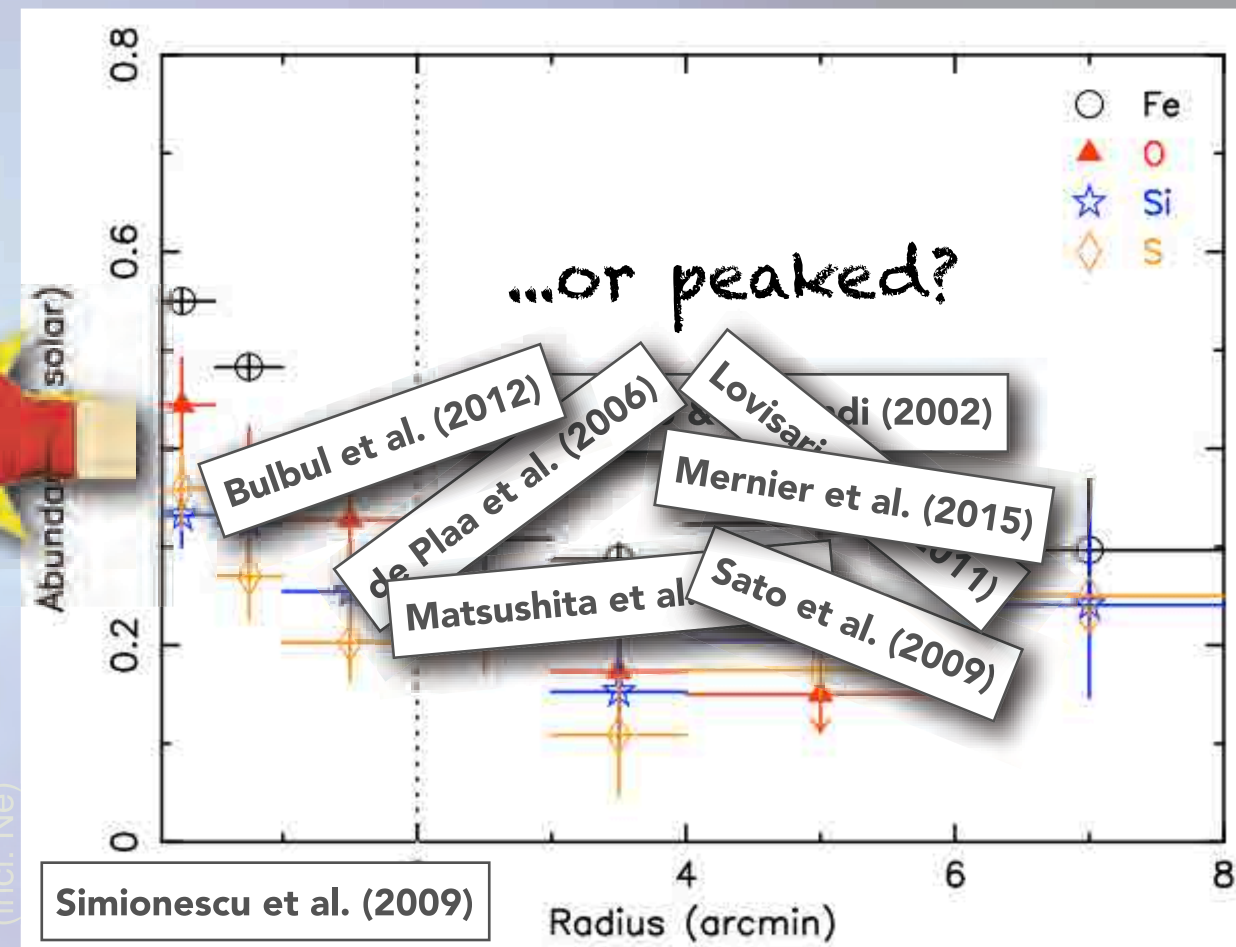




…how about other elements (SNcc products)?







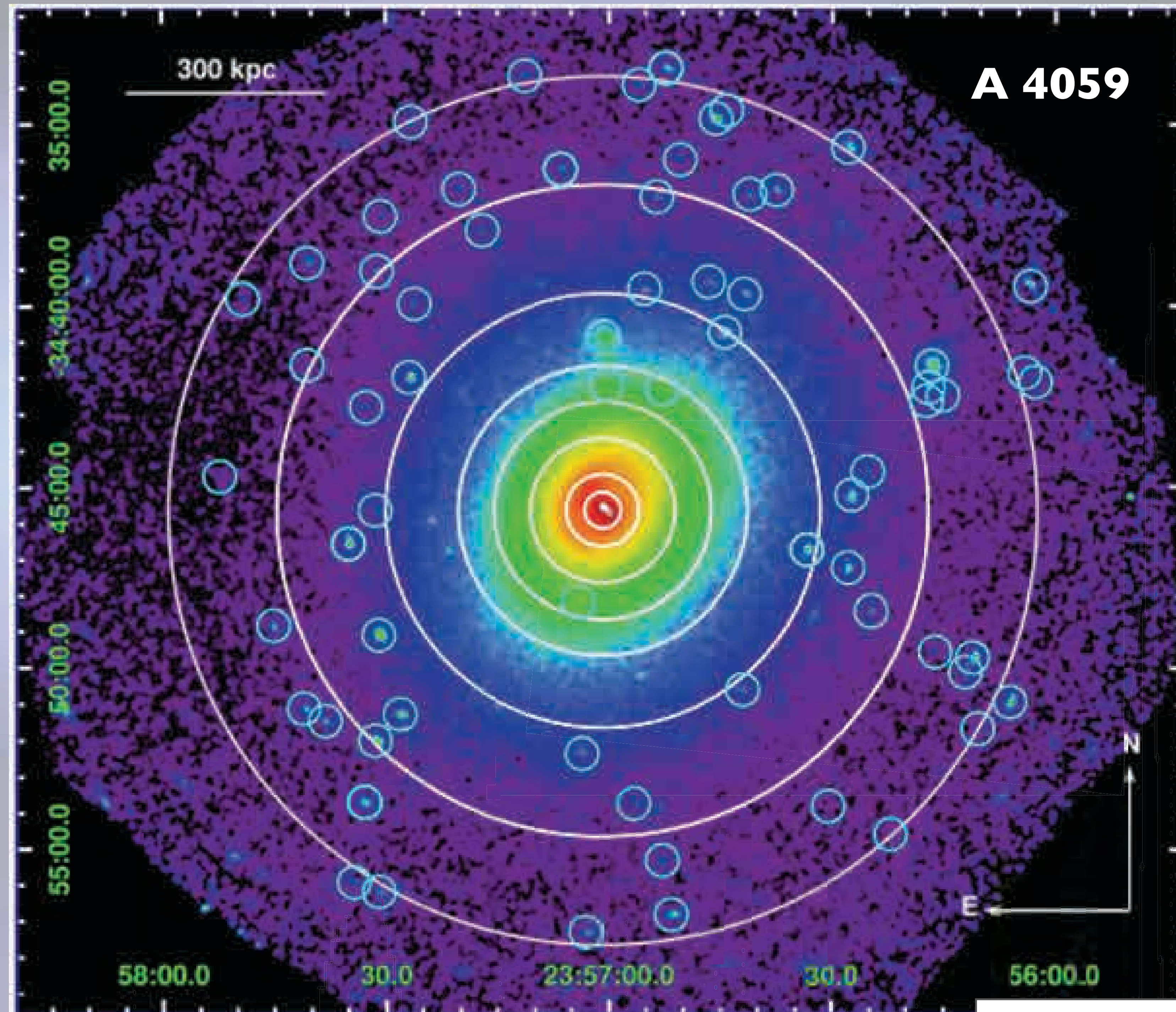
Various results about individual objects… But **no large, comprehensive study**!

Strategy (CHEERS sample)

EPIC

- Every pointing ➔ 8 concentric **annuli** (fixed angular sizes)

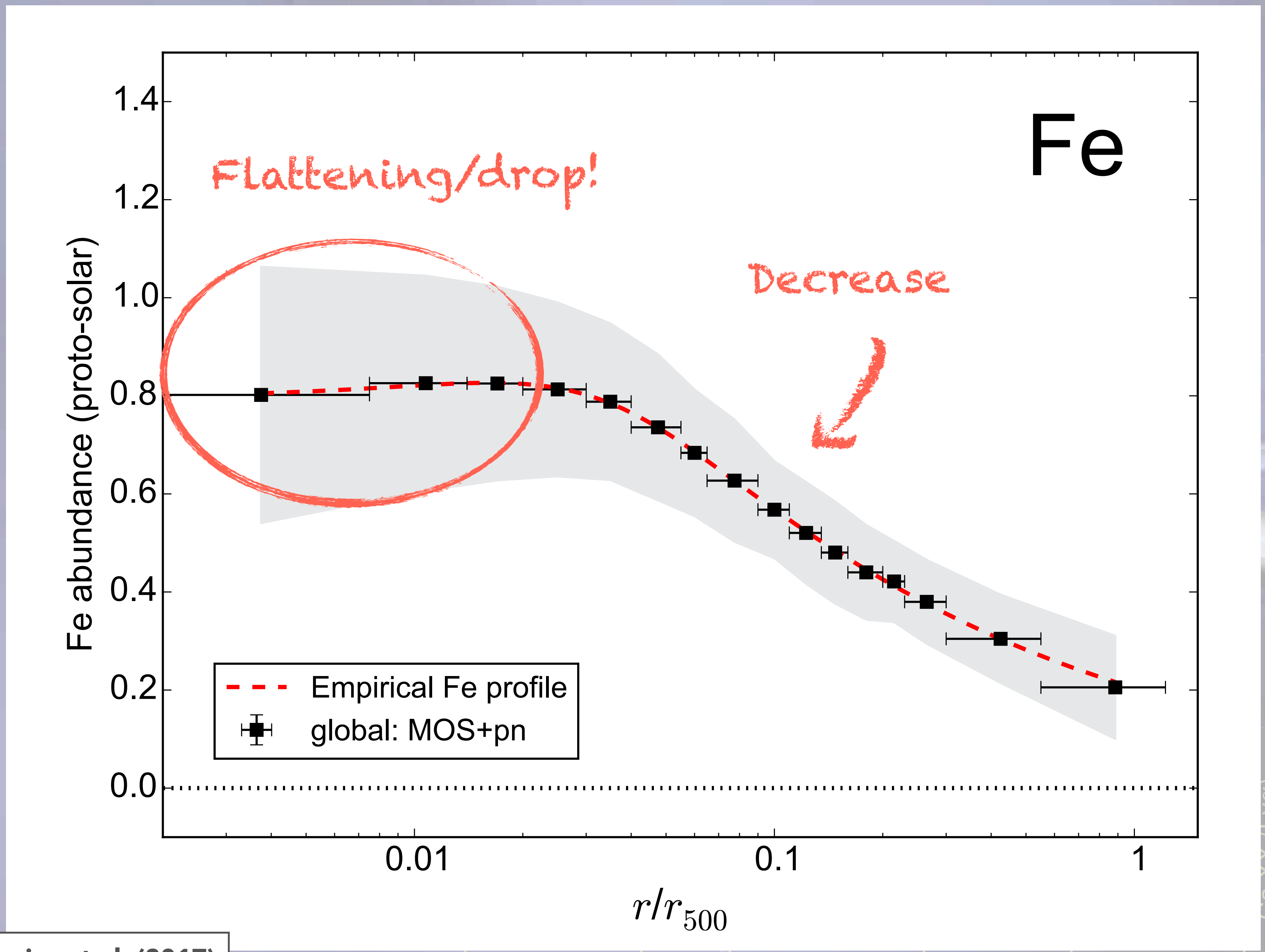
- **Stacking** all the measurements (in units of r_{500}, ~20 measurements per reference radial bin)



Mernier et al. (2015)

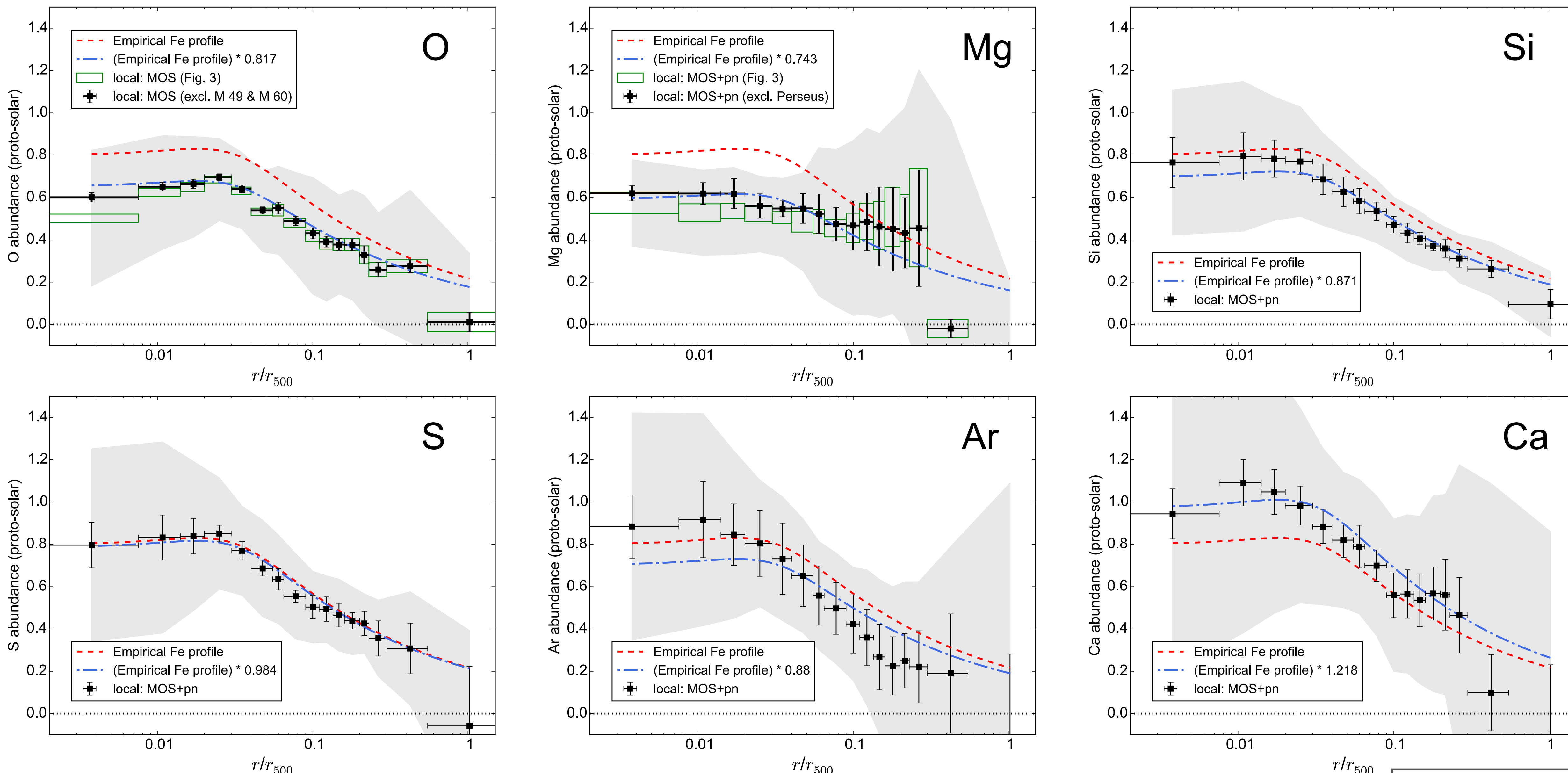
$\boldsymbol{r_{500}}$: radius within which mass density = 500 × (critical density of the Universe)

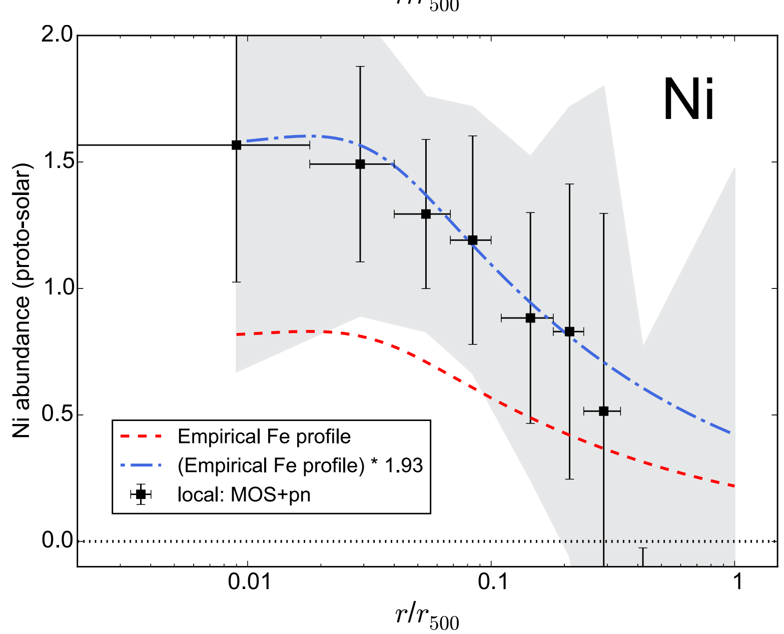
The (average) Fe profile



Mernier et al. (2017)

The abundance profile of other metals



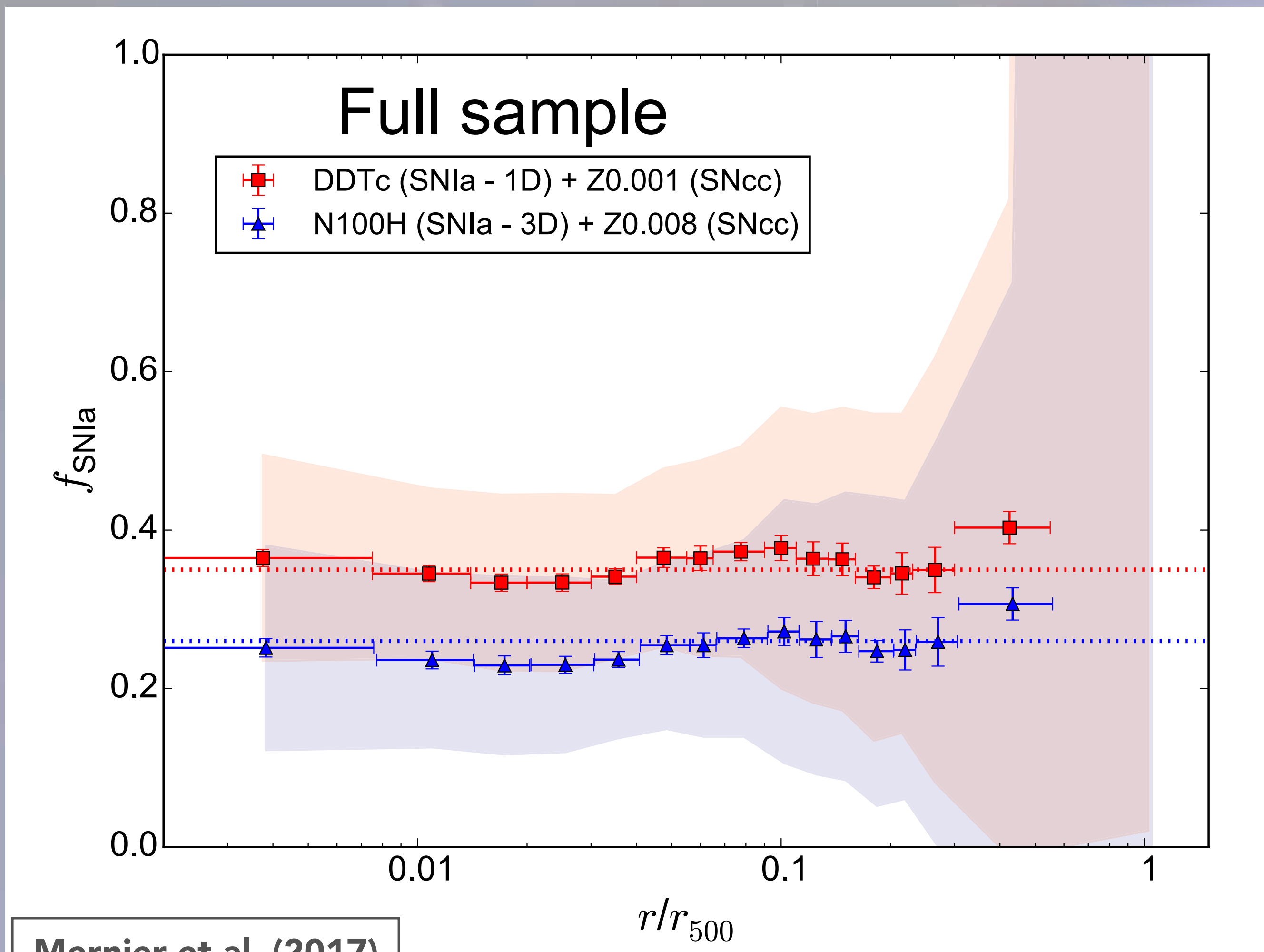


Mernier et al. (2017)

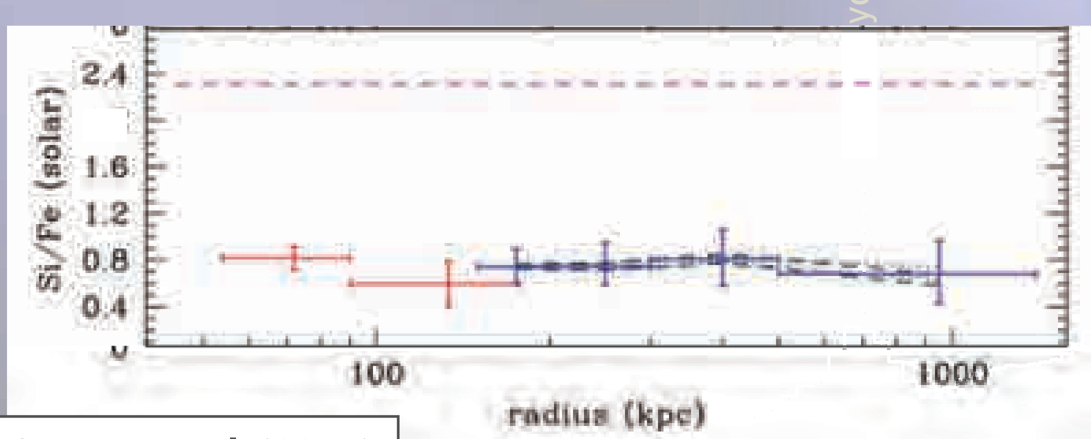
Systematic uncertainties under control:

- ✓ Projection effects
- ✓ Thermal modelling
- ✓ Background uncertainties
- ✓ Weight of individual observations
- ✓ Atomic code uncertainties

Radial distribution of the SNIa fraction



Mernier et al. (2017)



Simionescu et al. (2015)

Uniform f_{SNIa} fraction all across the ICM!

✓ <0.5 r500 **(Mernier et al. 2017)**

✓ >0.5 r500 **(Simionescu et al. 2015, Ezer et al. 2017)**

Implications:

➡ Even in the core, **SNIa and SNcc** have enriched the ICM at the **same epoch** and via the **same processes**

➡ **No** significant contribution from delayed SNIa in the BCG

- If central abundance peaks come from the BCG, they must have been produced **early on** (during the BCG formation; z>1)
  - Metals synthesised **in situ**? Or already in infalling, low-entropy **subhaloes**?
  - Contribution from **ram-pressure stripping**? **Intra-cluster stars**?

Summary so far

Chemical enrichment of the ICM...

➡ Where?

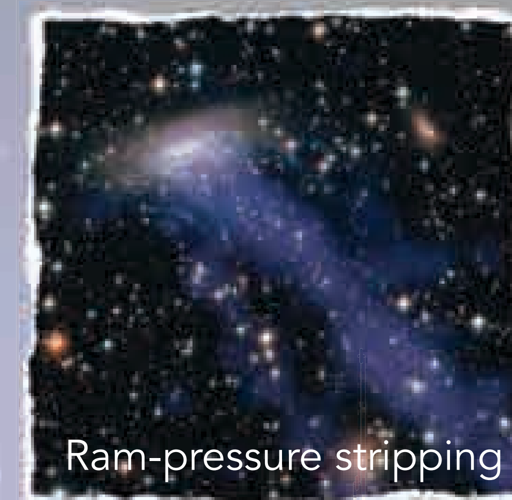
	Core	Outskirts
Cool-core	Central peak (SNIa and SNcc)	Flat distribution (~0.3 solar)
Non-cool-core	~Flat distribution	Flat distribution (~0.3 solar)

➡ When?

Core	Outskirts
During BCG formation (?)	Before cluster formation (> 10 Gyr ago)

➡ How?

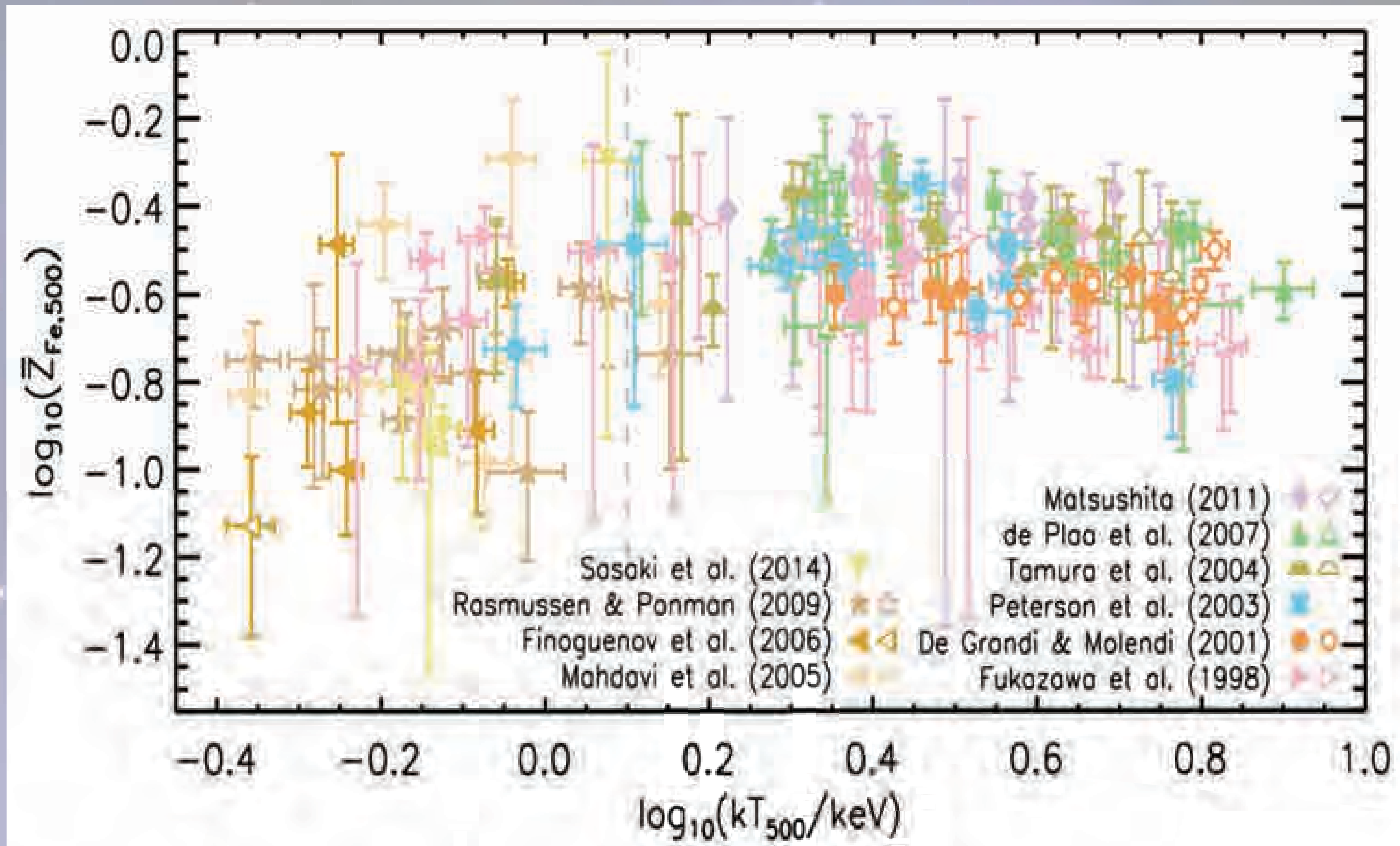
Core	Outskirts
• BCG? • Ram-pressure stripping? • Intra-cluster stars? • Galaxy mergers? • ...	• Galactic winds • Supermassive black hole feedback


Ram-pressure stripping


Galactic winds


Galaxy mergers

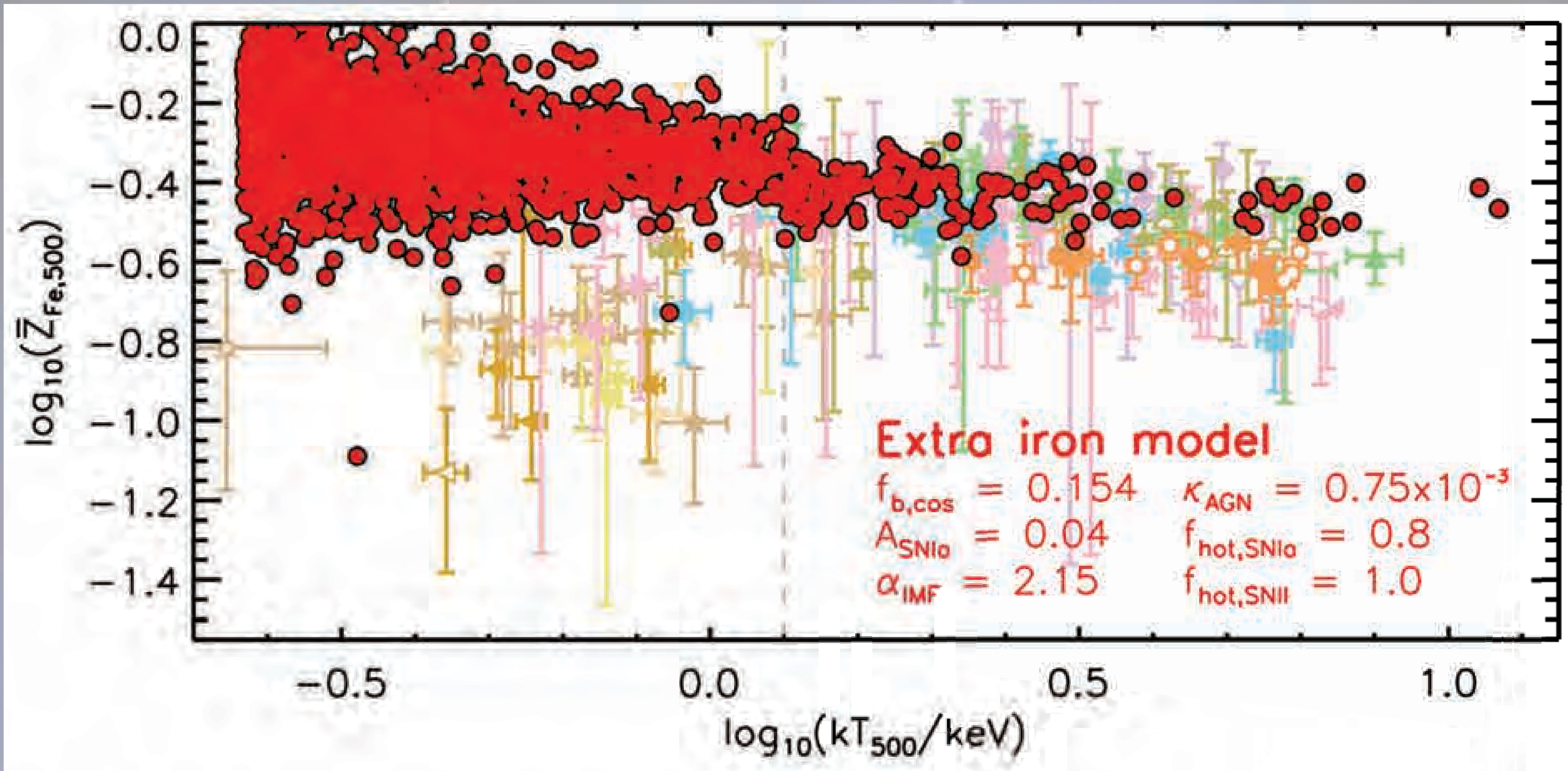
Enrichment in clusters vs. groups (and ellipticals)



Yates et al. (2017)

- Central Fe enrichment in groups/ellipticals appears **lower** than in clusters **(Rasmussen & Ponman 2009, Sun 2012, Yates et al. 2017)**

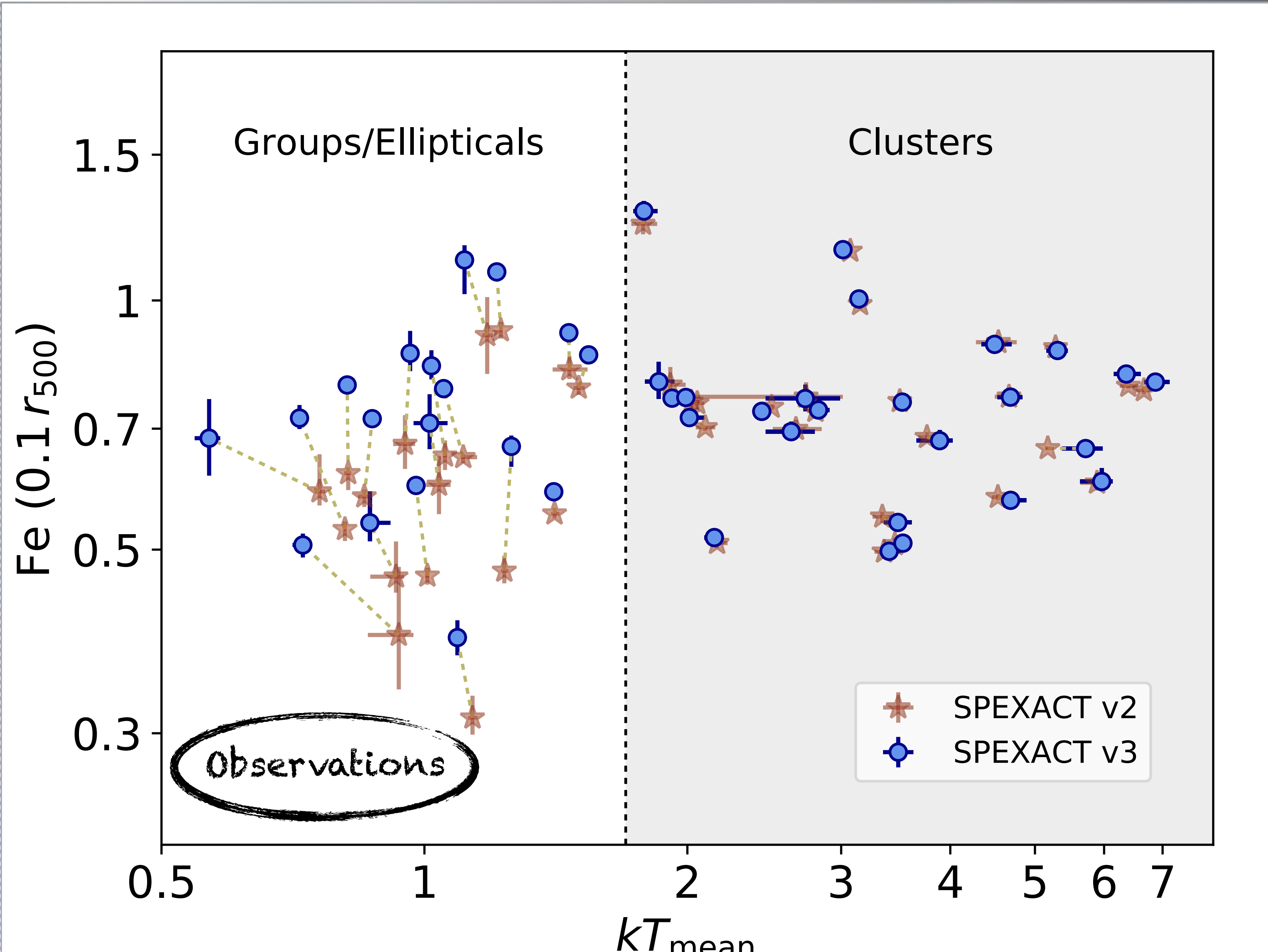
Enrichment in clusters vs. groups (and ellipticals)



Yates et al. (2017)

- Central Fe enrichment in groups/ellipticals appears **lower** than in clusters **(Rasmussen & Ponman 2009, Sun 2012, Yates et al. 2017)**
- Inconsistent with theoretical expectations! **(Yates et al. 2017)**

Enrichment in clusters vs. groups (and ellipticals)



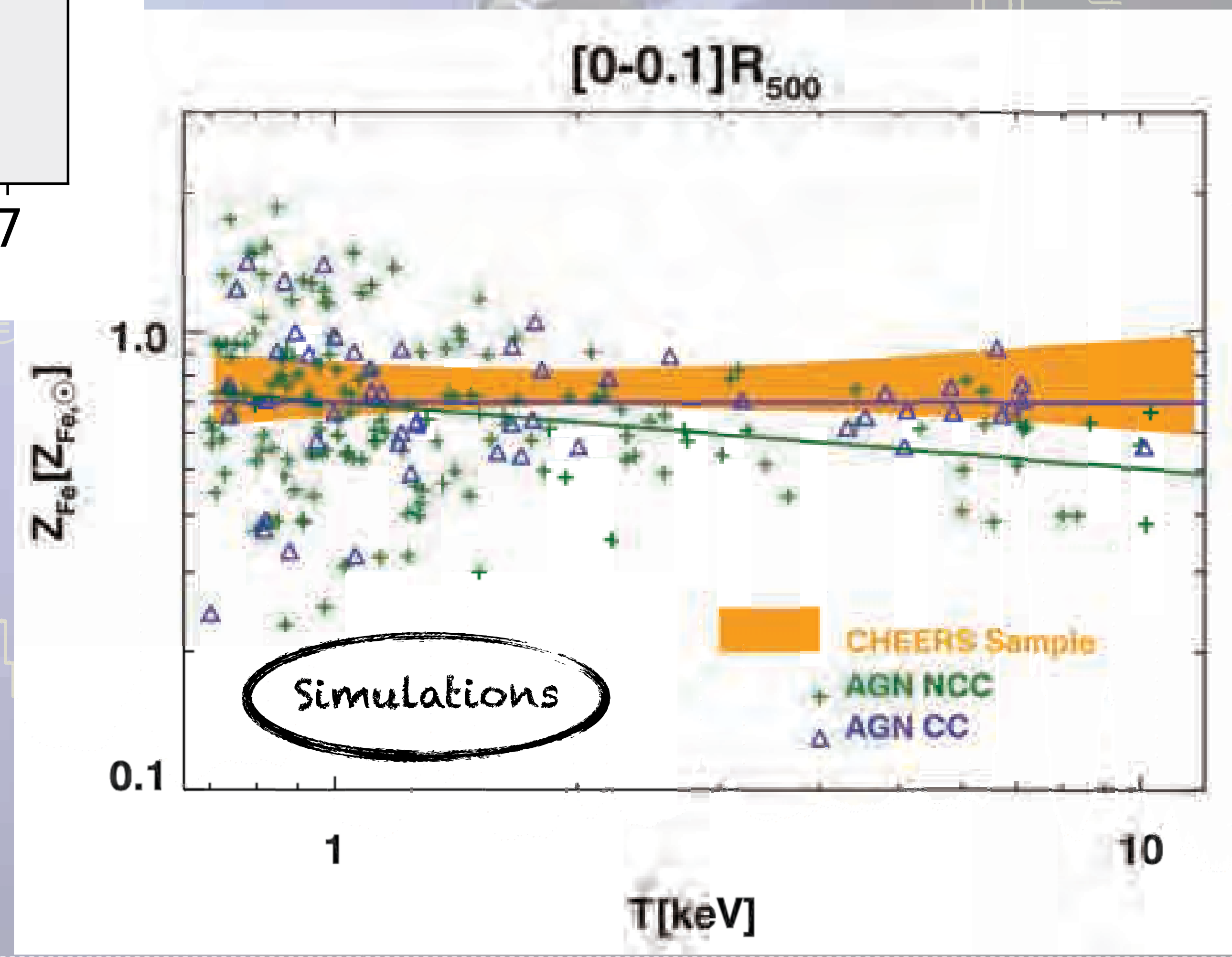
Mernier et al. (MNRAS Letters, in press)

For the first time, we find **similar central Fe abundances** between:

- **clusters**
- **groups**
- **ellipticals**

(2 orders of magnitude in total mass!)

Truong et al. (submitted)



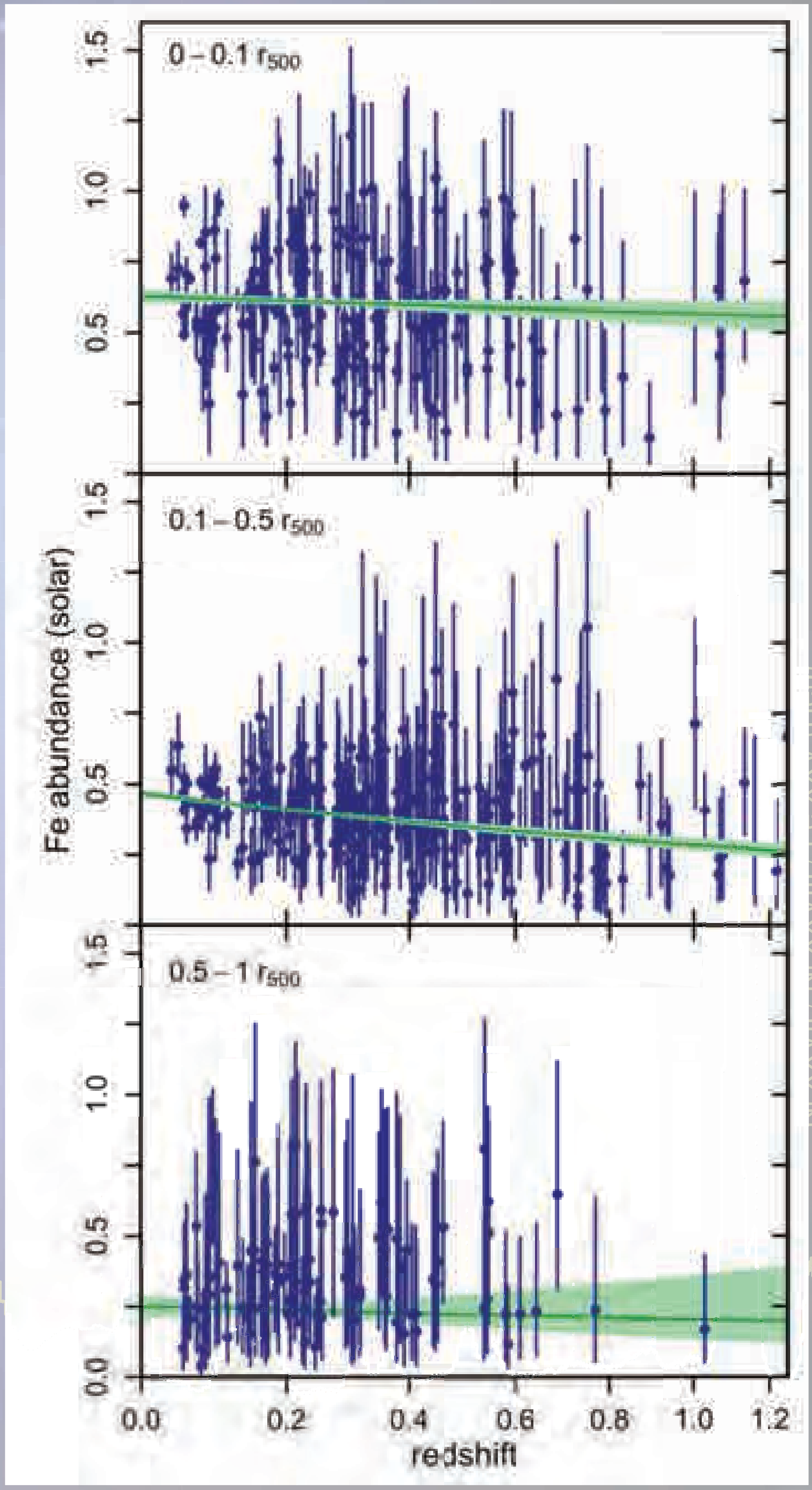
- High-z (proto-)clusters not so different from today's groups…

➡ Another hint for **early enrichment**?

Chemical evolution of the ICM

Does the Fe abundance (in the core and/or the outskirts) evolve with redshift?

- Many studies, but ***contrasted results***…
- Hints towards redshift evolution:
  - **Balestra et al. (2007); Maughan et al. (2008); Anderson et al. (2009)**
- No redshift evolution (up to z~1):
  - **Mushotzky & Loewenstein (1997); Tozzi et al. (2003); Baldi et al. (2012)**
- Most recent works **(Ettori et al. 2015; Mantz et al. 2017)**:
  - ***No*** signs of evolution in the outskirts, ***small*** evolution at intermediate radii and/or in the core

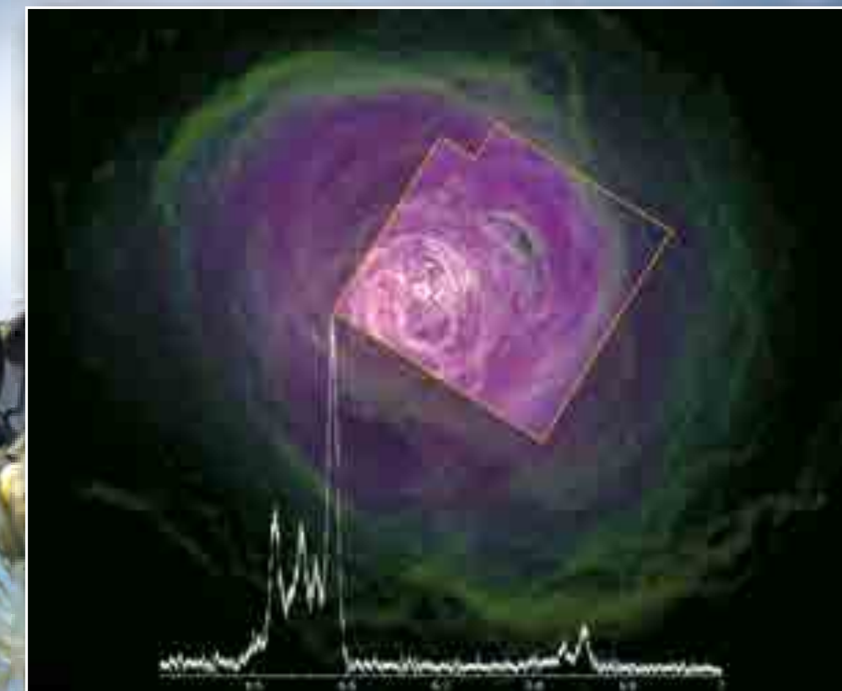


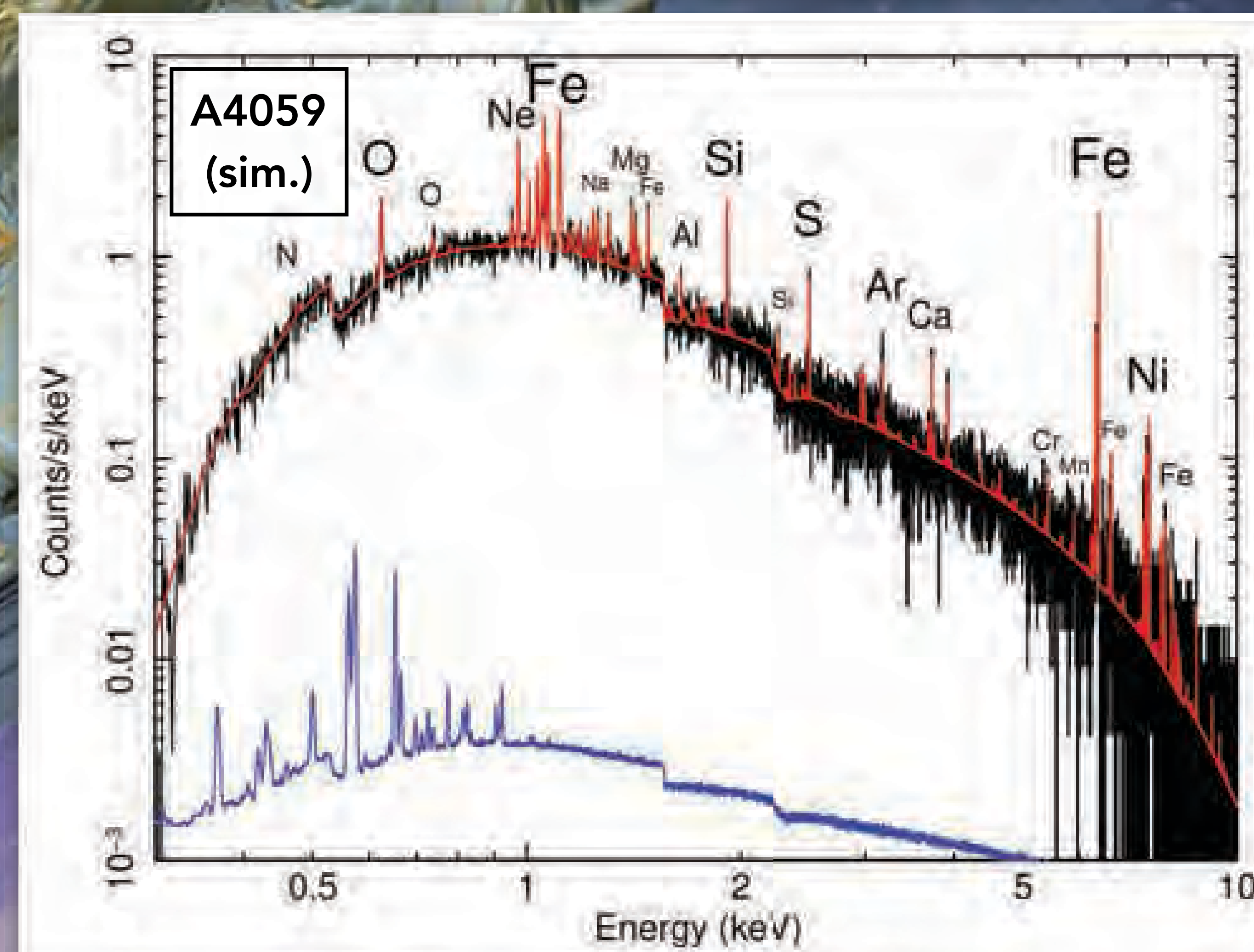
Mantz et al. (2017)

Future missions

X-ray Astronomy Recovery Mission (XARM)

- Re-launch of Hitomi
  - Demonstrated by Hitomi results!
    (see also Kitayama et al. 2014)
- Expected launch: 2021
- Dramatic improvement on the accuracy of many abundances
- Constrains on Na and Al
  ➔ ***Initial metallicities*** of SNcc progenitors?
- Constrains on Mn and Ni
  ➔ ***Explosion*** and ***progenitors*** of SNIa?

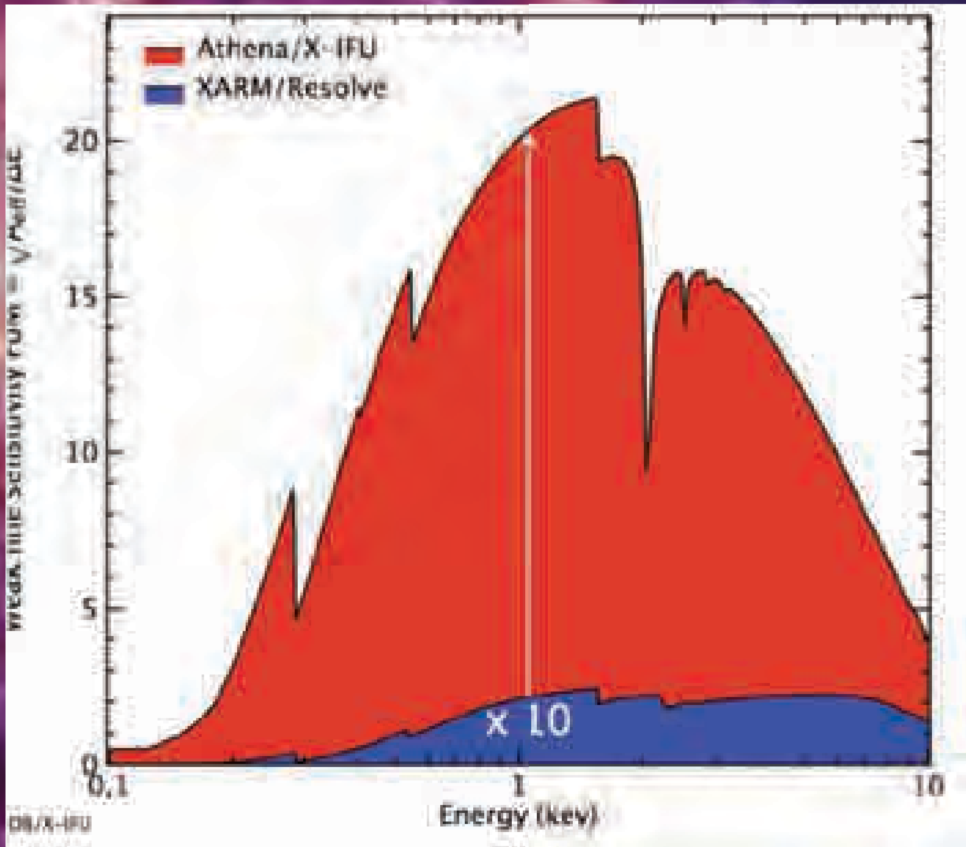


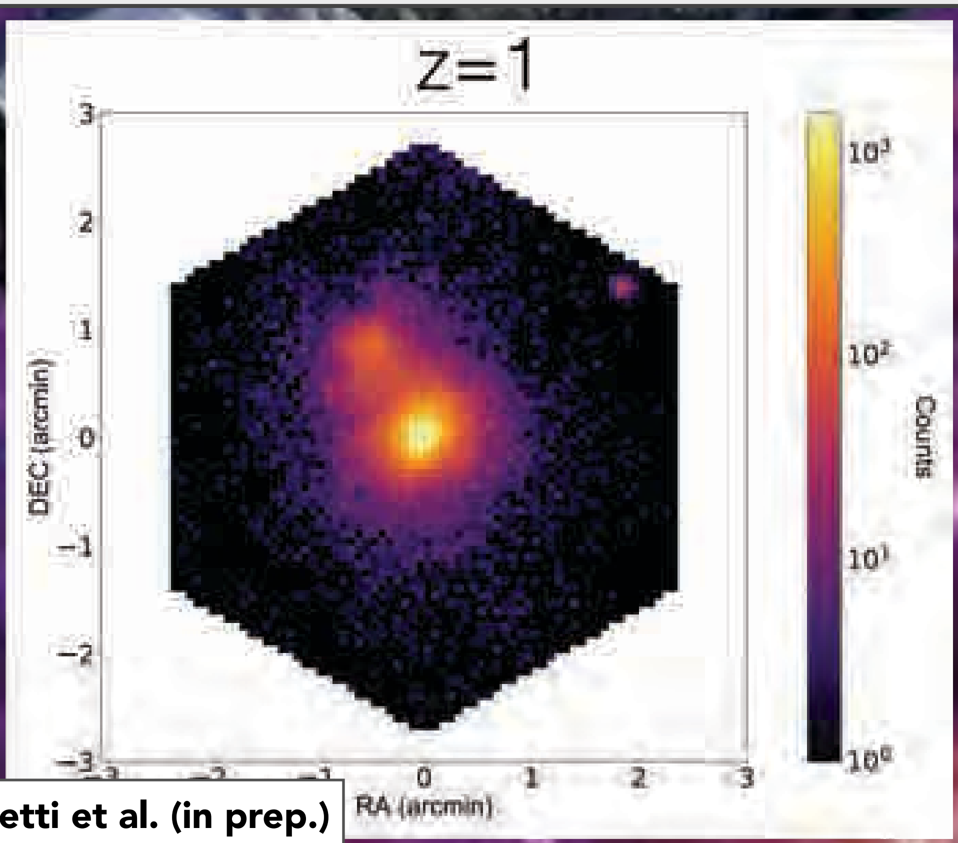


Athena

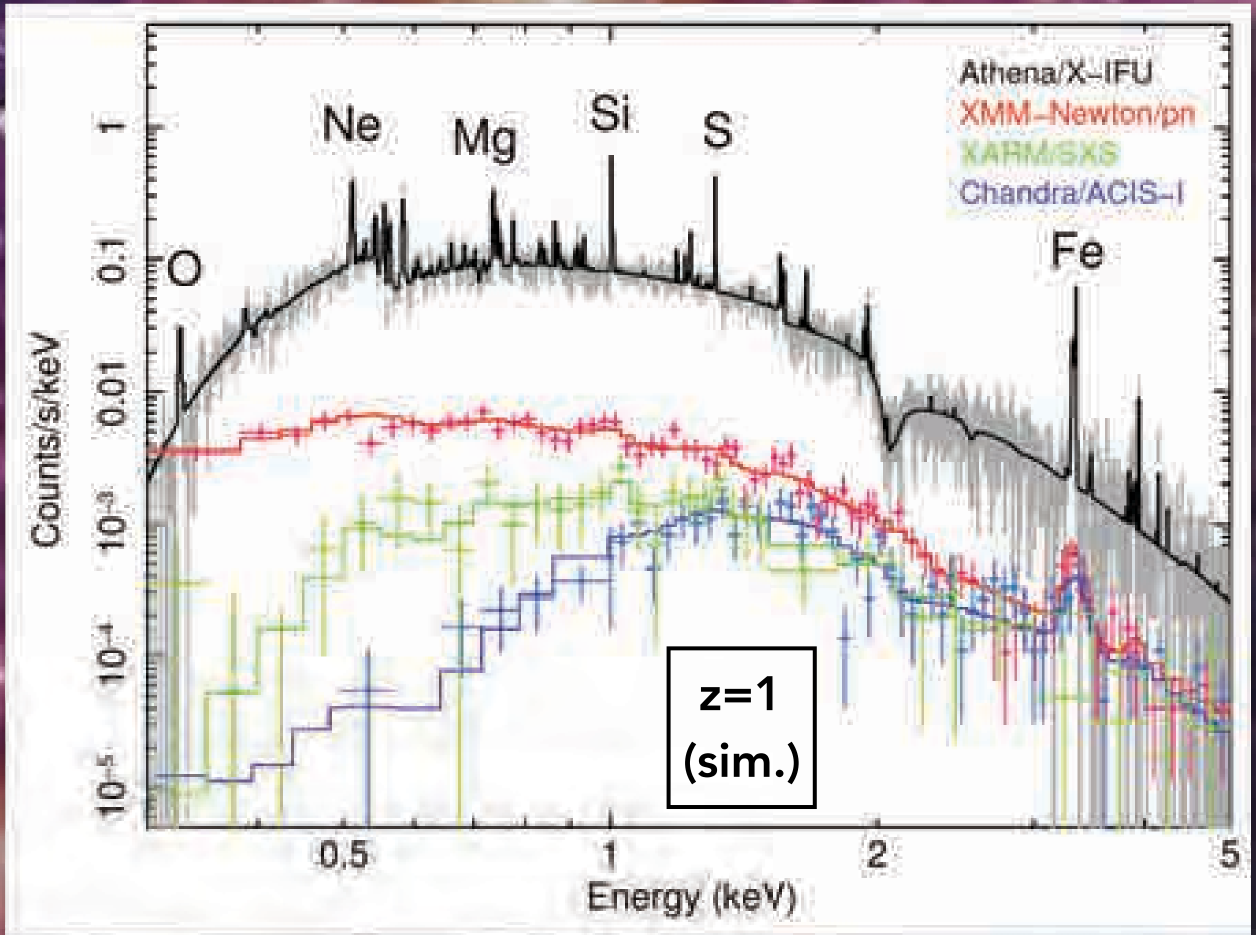
Athena

- X-IFU instrument onboard
  - **Barret et al. (2013); Ettori et al. (2013); Pointecouteau et al. (2013)**
- Expected launch: ~~2028~~ 2030?
- Great spectral resolution and sensitivity
- Convenient for ***redshift evolution*** of metals in the ICM



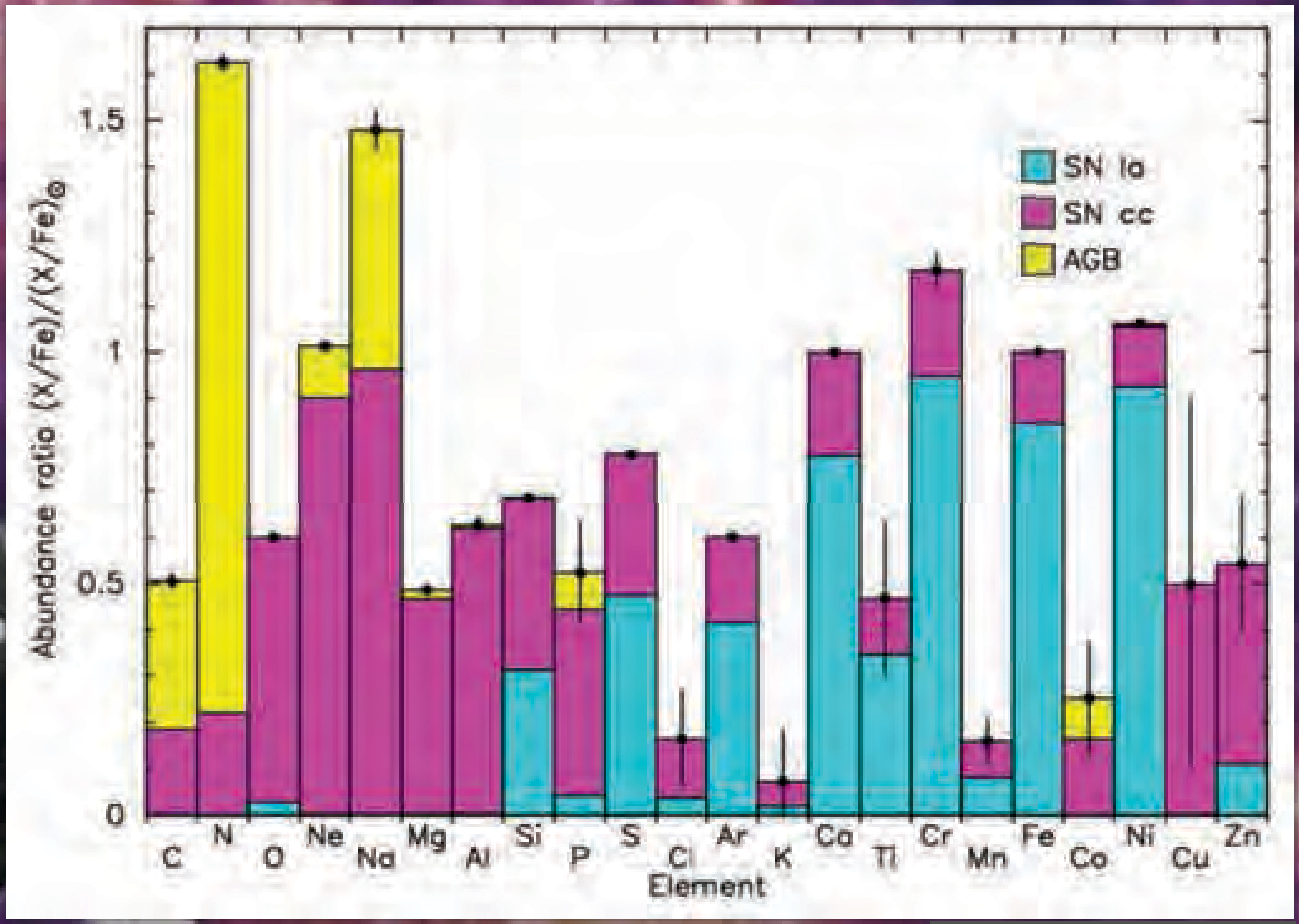


Cucchetti et al. (in prep.)



Athena

- X-IFU instrument onboard
  - **Barret et al. (2013); Ettori et al. (2013); Pointecouteau et al. (2013)**
- Expected launch: ~~2028~~ 2030?
- Great spectral resolution and sensitivity
- Convenient for ***redshift evolution*** of metals in the ICM



Ettori et al. (2013)

Improvements on

(i) Atomic codes

(ii) SNIa, SNcc, and AGB yields

are required!!

Conclusions

Conclusions

Take home messages

We can constrain supernovae (Ia & cc) properties by measuring the abundances in the hot intra-cluster medium

Outskirts: uniform distribution

→ **Very early enrichment** (z > 2-3: before cluster assembling)

(Cool) Core: centrally peaked distribution

→ **Early enrichment** (z > 1: during/shortly after BCG assembling)

From core to outskirts: SNIa vs. SNcc relative contribution does **not** change

→ Is the BCG really responsible for the central enrichment?

***From ellipticals to clusters:* Similar** average Fe enrichment

CHEERS!

The CHEERS collaboration

- ➡ ***Jelle de Plaa*** (P.I.) (SRON, Utrecht)
- ➡ François Mernier (Eötvös University)
- ➡ Jelle Kaastra (SRON, Utrecht)
- ➡ Hiroki Akamastu (SRON, Utrecht)
- ➡ Junjie Mao (SRON, Utrecht)
- ➡ Norbert Werner (Eötvös University)
- ➡ Aurora Simionescu (ISAS, JAXA)
- ➡ Yu-Ying Zhang (University of Bonn)
- ➡ Thomas Reiprich (University of Bonn)
- ➡ Gerrit Schellenberger (CfA Harvard)
- ➡ Lorenzo Lovisari (CfA Harvard)
- ➡ Hans Boehringer (MPE, Garching)
- ➡ Jeremy Sanders (MPE, Garching)
- ➡ Florian Hofmann (MPE, Garching)
- ➡ Ciro Pinto (IoA, Cambridge)
- ➡ Andy Fabian (IoA, Cambridge)
- ➡ Alexis Finoguenov (MPE, Garching)
- ➡ Kimmo Kettula (University of Helsinki)
- ➡ Jussi Ahoranta (University of Helsinki)
- ➡ Onno Pols (University of Nijmegen)
- ➡ Jacco Vink (University of Amsterdam)